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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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GEOCHEMICAL TABLE OF THE ELEMENTS FOR 1953

By Jack Green

Abstract

The geochemical table of the elements, with English, French, German, Spanish, and Russian key, contains the following data for each element:

Geochemical character.

Weight and structure—atomic number, atomic weight, weight of one atom, and electronic shell structure.

Size and charge—atomic and ionic radii, atomic and ionic volumes, ionization potentials, electrostatic valances, co-ordinations, and radius ratios.

Isotopic—naturally occurring isotopes with half lives and type of radiation decay.

Thermodynamic—standard heat of formation (gas), standard free energy of formation (gas), logarithm of equilibrium constant (gas), and entropy at 25° C. (gas and solid).

Mineralogic—common or geochemically significant minerals with per cent of element contained.

Value—cost per unit weight or volume.

Abundances in grams per metric ton—in sedimentary and igneous rocks; sea water (with transfer percentages); sulphide-, silicate-, and iron phase of meteorites; and the universe. Behavior during differentiation is shown in an idealized graph.

Series—electromotive, electronegativity, ionic potential, Hofmeister, Fournet and Schütz, Schürmann, and pH series.

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Introduction

The geochemical table of the elements represents a summary of progress in geochemistry up to the present.* The arrangement of the chart is that of the Periodic System including small offsets for subgroups. The modified periodic system of the ions of Efremov (1951; 1952) provides for a more systematic

* The following articles have appeared, the results of which are not included on Tables 2 or 3 but are abstracted below:

Behne, W., 1953, Untersuchungen zur Geochemie des Chlor und Brom: Geochimica et Cosmochimica Acta, v. 3, p. 186–215

Kuroda, P. K., and Sandell, E. B., 1953, Chlorine in igneous rocks: Some aspects of the geochemistry of chlorine: Geol. Soc. America Bull., v. 64, p. 879–896. (See table at foot of following page).

handling of the rare-earth ions but lacks the standard, well-known relationships of the atoms. From a genetic point of view, the periodic system of Meyer and Rosenqvist (1949a, p. 112–113; 1949b, p. 246) is commendable.

The table will be of use to geochemists, petrologists, mineralogists, economic geologists, and cosmogonists, especially in its application to problems concerned with the geochemical character of an element. Korzhinsky (1950) has applied the phase rule to such problems. The mobility of an element depends primarily on its electronic shell structure, but its behavior in an iron, sulphide, silicate, gaseous, or aqueous environment is the resultant of many factors, which are tabulated on the chart (Table 3). The role of iron in orthoclase feldspars, the mobility of zinc relative to lead, the possible ionic substitutions in phenacite, the number of electrons in the outermost quantum group of iodine, the abundance of thallium in shales, the precipitation of iron and its separation in weathering from manganese, the cosmic abundance of aluminum compared with its crustal abundance—these invite questions the geochemical table may help to answer.

All abundance data on the chart are in grams per metric ton. One metric ton (tonne, tonneau, millier, bar) is equal to one million grams or 2,204.62 avoirdupois pounds or 2,679.23 apothecary or troy pounds.[1] The following simple conversions obtain. One gram per metric ton equals:

One part per million (p.p.m.)
0.0001 per cent (%)
One microgram (μg or γ) per gram (g)
One $\times 10^{-6}$ grams per gram (g/g)
One milligram (mg) per kilogram (kg)
One thousand milligrams per cubic meter of water
One thousand micrograms per liter (l) of water.

To convert grams per metric ton to grams per cubic centimeter multiply grams per ton of igneous rocks by 2.8×10^{-6}; sandstones by 2.35×10^{-6}; shales by 2.5×10^{-6}; and limestones by 2.65×10^{-6}. These factors are based on specific gravities taken from Lange (1952, p. 1217–1218) and Grout (1940, p. 111, 190): igneous rocks—2.79; sandstones—2.35; shales—2.51; and limestones—2.65.

The writer is indebted to Dr. A. Poldervaart of the Department of Geology, Columbia University, for critically reviewing the manuscript and for valuable suggestions throughout most phases of progress of the geochemical table of the elements. Mr. V. Benavides and Mr. E. Alexandrov kindly provided the foreign translations of the key.

Principal Sources of Information

No attempt has been made to list all the data on every geochemical topic. The "best"

[1] One long or gross ton (U. S. or British) equals 2240 avoirdupois pounds or 2722.22 apothecary or troy pounds. One short or net ton (U. S.) equals 2000 avoirdupois pounds or 2430.56 apothecary or troy pounds.

	Behne		Kuroda and Sandell
	Chlorine	Bromine	Chlorine
	g/ton	g/ton	g/ton
Average Earth's crust			200
Average igneous rock	150	3.1	
Granitic rocks	200	1.3	220
Diorite and andesite	130	4.5	
Gabbro			210
Peridotite	40	1	
Basalt and diabase			140
Gabbro and basalt	60	3.6	
Syenite and trachyte	230	3.6	
Nepheline syenite and phonolite	330	1.9	
Ultramafics			50–2000 or more
Clay and shale	176	4	
Sandstone	10	1	
Limestone	122	6.2	
Dolomite	745	11.2	

data have been chosen, largely from personal prejudice influenced by various authoritative opinions. Main sources of information are taken from the references cited, and a more detailed evaluation of specific references is given below.

The following information is taken from the *Handbook of chemistry* (Lange, 1952): atomic weights, synonyms of elements, naturally occurring isotopes with half life and radiation decay, thermodynamic data, and value per unit weight or volume. The weight of one atom has been computed using 6.0228×10^{23} for Avogadro's number. Ionic radii and some gaseous ionization potentials are taken from Ahrens (1952, p. 168–169 and 159). Atomic radii are mostly from Lange (1952, p. 121–123). Atomic and ionic volumes, co-ordinations, radius ratios, and electrostatic valances have been computed from these radii using a 1.40 Å radius for oxygen as basis for calculation.

Common or geochemically significant minerals with per cent element contained were obtained from various mineralogic textbooks. In many cases the per cent element has been computed from oxide weight percentages. Many data were taken from Seeton (1949), while uranium values were derived from George (1949, p. 162) and Page (1950, p. 16–19).

Costs of pure elements are compiled from Lange (1952, p. 58–90) and current chemical catalogs.

Geochemical character of elements is taken from Rankama and Sahama (1950, p. 91) and Mason (1952, p. 52). Rankama and Sahama (1950, p. 796–797), supplemented by Lange (1952, p. 57, for Bk and Cf), are the sources for the electronic structures of the elements.

Meteoric data for the sulphide, silicate, and metal phase are obtained from Brown (1948, p. 626). Some of these data, quoted from Noddack and Noddack (1930, p. 759), may bear revision. Cosmic abundance data are recalculated from Urey (1952b, p. 252). Bracketed numbers indicate other sources. The use of chondrite analyses for averages of cosmic abundances (*i.e.*, the nonvolatile constituents of the cosmos) is an interesting way of avoiding weighting the silicate, iron, and sulphide meteoritic phases in untenable ratios. The remarkable uniformity of concentration of many elements in chondrites also speaks in its favor. Urey's hypothesis on planet origin (Urey, 1952a) is supported by the fact that chondrite meteorites have nearly the same density as the moon. Urey notes that Fe, Hg, Se, Te, Br, and I are low compared with other cosmic abundance data. Hg, and possibly Te, Se, Br, and I may be low because of their volatility.

Data for nonradiogenic isotopes are taken from Ingerson (1953).

Terrestrial abundances are derived from Rankama and Sahama (1950) and are brought up to date from additional references. Abundances of common elements in sediments may need revision if Sujkowski's data (1952) are valid.

The electromotive, electronegativity, ionic potential, Schürmann, Hofmeister, "standard" zoning and pH series yield information of value to geochemists. The electromotive series is compiled from Lange (1952, p. 1243-1249) and Hodgman (1951, p. 1465–1467) on the basis of standard electrode potentials at 25° C. Mason (1949) discusses their applicability to geological processes. The electronegativity series is compiled by Fyfe (1951, p. 540) from Pauling (1944, p. 64) and Haissensky (1946, p. 10). The green curve on the chart represents the electronegativity of the chlorides as determined by C. H. Townes and B. P. Dailey (personal communication) and may well give a more exact picture of the actual electronegativity curve. The ionic-potential graph is constructed from data on the chart. The colored lines divide the graph on the chart into three fields (which overlap in nature): the soluble cations characterized by ionic bonds (electrostatic valence less than ½); the hydrolyzates characterized by the hydroxyl bond (electrostatic valence between ½ and 1); and the soluble anion complexes (electrostatic valence greater than 1) (Wickman, 1944). A discussion of the significance of ionic potential is given by Mason (1952, p. 137–142) and Rankama and Sahama (1950, p. 236–240). The Hofmeister series, Fournet and Schütz series, and the zoning series are taken from Rankama and Sahama (1950, p. 242, 696, 183). Schürmann's series is from Lindgren (1933, p. 826). The table of pH values is compiled from Mason (1952, p. 140) and Barth (1950, p. 44).

Selected Data and References

RADII: Xe, Kr, F, and P atomic radii, and Ac^{+4} and S^{-2} ionic radii are from Lange (1952, p. 121–123). The radius of F^{-1} is that used by Ramberg (1952, p. 275–290) in his section on chemical bonds in crystals. All other atomic and anionic radii are from Lange (1952, p. 121–123) and Rankama and Sahama (1950, p. 794–795). Th^{+4}, Eu^{+2}, and Yb^{+2} are also from Rankama and Sahama; the last two are based on a radius of 1.33 Å for oxygen. All other ionic radii on the chart are derived from ionization potentials (Ahrens, 1952), and all other radius functions are based on a radius of 1.40 Å for oxygen. The atomic radius for Rn is extrapolated. Ahrens (1953, p. 23) cautions that ionic radii may be used in a restricted way in sulfide minerals.

IONIZATION POTENTIALS (GASEOUS): Ionization potentials are taken predominantly from Lange (1952, p. 275–290) supplemented by those listed in Ahrens (1952, p. 159).

THERMODYNAMIC DATA: Entropies for carbon are those of graphite, not diamond. Eitel (1952) has compiled information on thermodynamic properties of the silicates, and further data are given in Circular 500 of the National Bureau of Standards on Selected Thermodynamic Values of Chemical Properties edited by Rossini (1952).

ISOTOPIC DATA: Relative per cent abundances for naturally occurring isotopes of Tl and Lu are not given by Lange (1952, in compilation by J. R. Stehn) and are taken from Seaborg and Perlman (1948, p. 626–630). Only naturally occurring isotopes and their (terrestrial) relative per cent abundances are recorded on the chart.

ABUNDANCES IN IGNEOUS ROCKS: Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, and Hg (upper limit) abundances in igneous rocks are values for shale from Minami (1935, p. 168–169) and Stock and Cucuel (1934, p. 391), quoted in Rankama and Sahama (1950, p. 510, 717), and are identified by a question mark. The numbers are rounded off to one decimal place because of the uncertainty of allotting shale abundance values to igneous rocks. In some cases (*e.g.*, Sc, Ce, Y, Nd, and La) van Tongeren's values (1938, p. 178) for abundances in igneous rocks of the Indonesian Archipelago were used in preference to abundance values in shales. The abundance values for rare earths in Anderson (1942, p. 331), Clarke and Washington (1924, p. 22), and Noddack and Noddack (1930, p. 759; 1936, p. 2) were not assumed to include Pm, the abundance value of which has not been determined. The value of .10 g/ton for Ag in igneous rocks (Rankama and Sahama, 1950, p. 702) is changed to .1 g/ton as given by Goldschmidt (1937b, p. 656). Abundance data of Po, Ra, Ac, and Pa are based on a uranium content of 4 g/ton in igneous rocks. Holland (1952, p. 14) gives for the average uranium content of rocks exposed to subaerial weathering the value of 2.5 ± 0.5 g/ton. Recent values for Ga (Sandell 1949, p. 40), Be (Sandell, 1952, p. 211), Zn (Wedepohl, 1953, p. 137), Tl (Shaw, 1952a, p. 152), Rb, and K (Ahrens, Pinson, and Kearns, 1952, p. 229) are included. Behavior during differentiation is brought up to date with regard to K in ultramafics (Holyk and Ahrens, 1952, p. 1264); Ra in ultramafics (Davis, 1947, p. 690–691); Sc in diabase (Fairbairn *et al.*, 1953, p. 44) Ga and Zr in basic rocks (Ahrens and Gorfinkle, 1950, p. 565); Ba, Sr, Sc, and Zr in ultramafics (Pinson and Ahrens, 1952, p. 1290); and Ra and Th in basic and granitic rocks and sediments in compilation by Gutenberg (1951, p. 153).

ABUNDANCE DATA OF SEDIMENTS: K, Rb, Cs, and Tl in shales are recalculated from Canney (1952, p. 1238). Sr in limestones is recalculated by Mr. K. Turekian (personal communication) from Kulp, Turekian, and Boyd (1952, p. 701). Some of the values for W, Rb, La, Ce, Sc, Y, Ni, and Nd in sedimentary rocks result from analyses of metamorphosed carbonates, quartzites, and schists of southern Lapland. They are identified by a question mark. Abundance of Zn in shales includes deep-sea argillic sediments (Wedepohl, 1953, p. 139).

METEORITIC PHASES: Bi and Os for the silicate phase, W in the troilite phase, and Re for all three phases are quoted from Rankama and Sahama (1950). All other data are from Brown (1949, p. 626). Shaw (1952a, p. 151) finds Tl extremely low in meteorites. Radium content of meteorites is taken from Davis (1950, p. 110). Much detailed work has been done on the distribution of Ni, Co, Ga, Pd, and Au in iron meteorites (Goldberg, Uchiyama, and Brown, 1951).

OCEANIC ABUNDANCES: These data are based

on a chlorinity of 19.00. Hg and Sc are quoted from Goldschmidt (1937b, p. 666–667); Cu from Noddack and Noddack (1940, p. 33); Mo from Ernst and Hörmann (1936, p. 208); Th from Koczy (1949, p. 241); Ra and U from Rona and Urry (1952, p. 249) and Se from Trelease and Beath (1949, p. 116). All other data are from Sverdrup, Johnson, and Fleming (1942, p. 176–177) and Harvey (1945, p. 31–32). Argon is measured from the residue after the extraction of nitrogen. Values not included on the chart are:

CO_2—34–56 ml/l
NH_3—.005–.05 ml/l
Fe (in true solution)—1×10^{-9} g/ton
Ionium (Holland, 1952, p. 28)—$3.1 \pm 1 \times 10^{-9}$ g/ton (calculated).

The value for Fe on the chart is particulate iron (Harvey, 1945, p. 35).

TRANSFER PERCENTAGE: This number is calculated from maximum abundances in the ocean and the total amount supplied to the sea. The last is based on the assumption that 600 grams of average igneous rock are weathered for each kilogram of ocean water (Goldschmidt, 1937b, p. 666). The transfer percentage pertains to the maximum quantity supplied to the sea. Where several values are quoted an arrow indicates the value from which the transfer percentage has been derived. The transfer percentage for Th is calculated from Koczy (1949, p. 241) and 6.9 g/ton supplied to the sea, as quoted in Rankama and Sahama (1950, p. 295). The transfer percentage for Ra and U is calculated from Rona and Urry (1952, p 249) and the maximum amount supplied to the sea quoted in Rankama and Sahama (1950, p. 295).

COSMIC ABUNDANCE: Values not in brackets are taken from Table 1 in Urey (1952b, p. 252) with the exception of Po, Ac, Pa, and Ra, which are taken from Rankama and Sahama (1950, p. 782–783). Th is from Goldschmidt (1937a, p. 122); U (based on two achronites) from Davis (1950, p. 110); and H, He, Ne, C, N, O, and A recalculated by Urey from Kuiper (1952, p. 329). Bracketed values include Sr, B, Sc, and Zr in chondrites (Pinson and Ahrens, 1952, p. 1210); Rb in chondrites (Ahrens, Pinson and Kearns, 1952, p. 239); Th in silicate meteorites (Brown, 1949, p. 626) and Ce, calculated (Suess, 1949, p. 268).

All cosmic abundance data have been recalculated to grams per metric ton for comparison with other abundance information. The number of atoms per 10,000 Si atoms used in cosmic abundance tables has been multiplied by the atomic weight of each element, totalled, and recalculated to 100 per cent. The results have been converted to g/ton for each element. Numbers for Po, Ac, Pa, Ra, and Th (both values) are based on their content in the silicate phase of meteorites, first normalized to grams per 10,000 Si atoms. Urey's value of 17.96 per cent for the Si content of the average chondrite is used as basis for the calculations (Urey, 1952b, p. 252). Thus:

$$\text{atoms of element Z per 10,000 Si atoms relative to the average chondrite meteorite} = \frac{\text{grams/ton} \times 280{,}900}{\text{atomic weight of Z} \times 179{,}600}$$

NONRADIOGENIC ISTOPE DATA: Ingerson (1953) and Bainbridge and Nier (1950) give reviews of the relative isotopic abundances of the elements. Specific sources for the isotopic information on the chart are given in the bibliography and are identified by an asterisk.

DEFINITION OF TERMS

Chondrite: "a general term for meteoric stones which contain chondrules [spherical aggregates] embedded in a finely crystalline matrix consisting essentially of pyroxene (mainly enstatite or bronzite), olivine, and nickel-iron with accessory troilite, chromite, and oligoclase. Glass (maskelnyite?) is sometimes present and in the chondrules may even become abundant" (Holmes, 1920, p. 58).

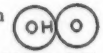
Electrode potential: also called redox potential, oxidation-reduction potential, reduction potential, or oxidation potential: A measure of the energy of oxidation or the electron-escaping tendency of a reversible oxidation-reduction system with reference to the reaction:

$$H_2 \rightleftharpoons 2H^- + 2e$$

which is arbitrarily fixed at zero volts.

Electronegativity: a pure number; the resultant of the factors of ionization potential

TABLE 1.—BOND TYPE CORRELATED WITH MINERAL TYPE AND PHASE OF DIFFERENTIATION
(Bond characteristics modified after Evans, 1939, p. 40)

Mineral type	Partition phase	Bond type	Bond characteristics				
			Mechanical	Thermal	Electrical	Optical and magnetic	Structural
The Metals (Siderophile)	1	Metallic	Variable strength Gliding common	Variable melting point Long liquid interval	Conduction by electron transport	Opaque. Properties similar in liquid	Nondirected, giving structures of very high co-ordination and high density
Sulphides (Chalcophile)	1	Homopolar	Strong, giving hard crystals	High melting point, low coefficient of expansion. Molecules in melt	Insulators in solid and melt	High refractive index. Absorption profoundly different in solution or gas	Spatially directed and numerically limited, giving structures of low co-ordination and low density
Hydrolyzates and precipitates (Predominantly Lithophile)	3	Hydroxyl	Breakdown of polar OH groups giving place to structures of tetrahedral symmetry. Not a resonance structure. Weaker than hydrogen bond.				
	3	Hydrogen	Symmetrical bond to be regarded as a resonance between  and Ionic in character. (Actually four types of hydrogen bond exist (Coulson, 1952, p. 299). The one shown is most important geochemically.)				
Silicates (Lithophile)	1 and 2	Ionic	Strong, giving hard crystals	Fairly high melting point. Low coefficient of expansion. Ions in melt.	Moderate insulators. Conduction by ion transport in melt. Sometimes soluble in liquids of high dielectric constant	Absorption and other properties primarily those of the individual ions and therefore similar in solution	Nondirected, giving structures of high co-ordination
		Van der Waal	Weak, giving soft crystals	Low melting point	Insulators	Properties those of the individual molecules	Formally analogous to the metallic bond

					stant		
		Van der Waal	Weak, giving soft crystals	Low melting point High coefficient of expansion	Insulators	Properties those of the individual molecule and therefore similar in gas and solution	Formally analogous to the metallic bond

and electron affinity which determines the bond type formed. The greater the difference in electronegativity the more ionic is the bond; the smaller the difference the more homopolar is the bond (Pauling, 1945, p. 58; 1948, p. 1461).

Distribution of the Elements

Probably no single concept influences geologic thinking more profoundly than the distribution of elements in space and time. Goldschmidt

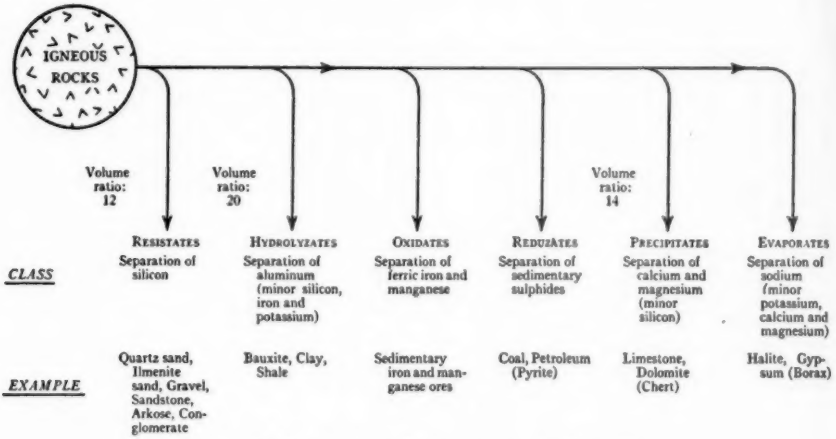


Figure 1.—Geochemical Separation of the Elements

Modified after Rankama and Sahama (1950, p. 199). Volume ratios of sandstones to shales to limestones taken from Kuenen (1950, p. 387).

Electrostatic valence: ionic charge divided by the co-ordination; a measure of the behavior of an ion toward water and analogous to ionic potential.

Ionic potential: charge divided by radius; a measure of the intensity of positive charge on the surface of the ion—*i.e.*, a measure of the behavior of an ion toward water (Cartledge, 1928, p. 2856; Noll, 1931, p. 557; Goldschmidt, 1934, p. 408; Wickman, 1944, p. 1).

Ionization potential (gaseous): the amount of energy, usually expressed in volts, needed to remove an electron completely from an atom.

Nutrient line: the line drawn on the periodic table from K via C to Fe which passes through or near all the elements essential for life (Frey-Wyssling, 1935, p. 768).

Radius ratio: the ionic radius divided by the ionic radius of O^{-2} (1.40 Å in this paper). The co-ordination depends upon the radius ratio.

Transfer percentage: the amount of an element present in sea water divided by the total amount of that element supplied to the sea; a measure of relative enrichment of the element in sea water.

(1926; 1930; 1933) first formulated the principles governing this distribution. In somewhat modified form his views are abstracted below:

Phase 1—Partition of elements during the creation of cosmic bodies; each element preferentially distributing itself in an iron melt, sulphide melt, silicate melt, or a gas. This partitioning is influenced strongly by conditions of high enthalpy where bond type is the most important factor. Partition of the elements is as follows:

Iron melt	*Sulphide melt*	*Silicate melt*
Predominantly metallic bonds	Predominantly homopolar bonds	Predominantly ionic bonds
Siderophile elements	Chalcophile elements	Lithophile elements

Quantum mechanics postulates that there exists a continuum of bonding energies (Evans, 1939, p. 41). These bonding energies are intensified by environmental conditions ideally into one of the four bond types: the ionic, homopolar, metallic, and the van der Waal

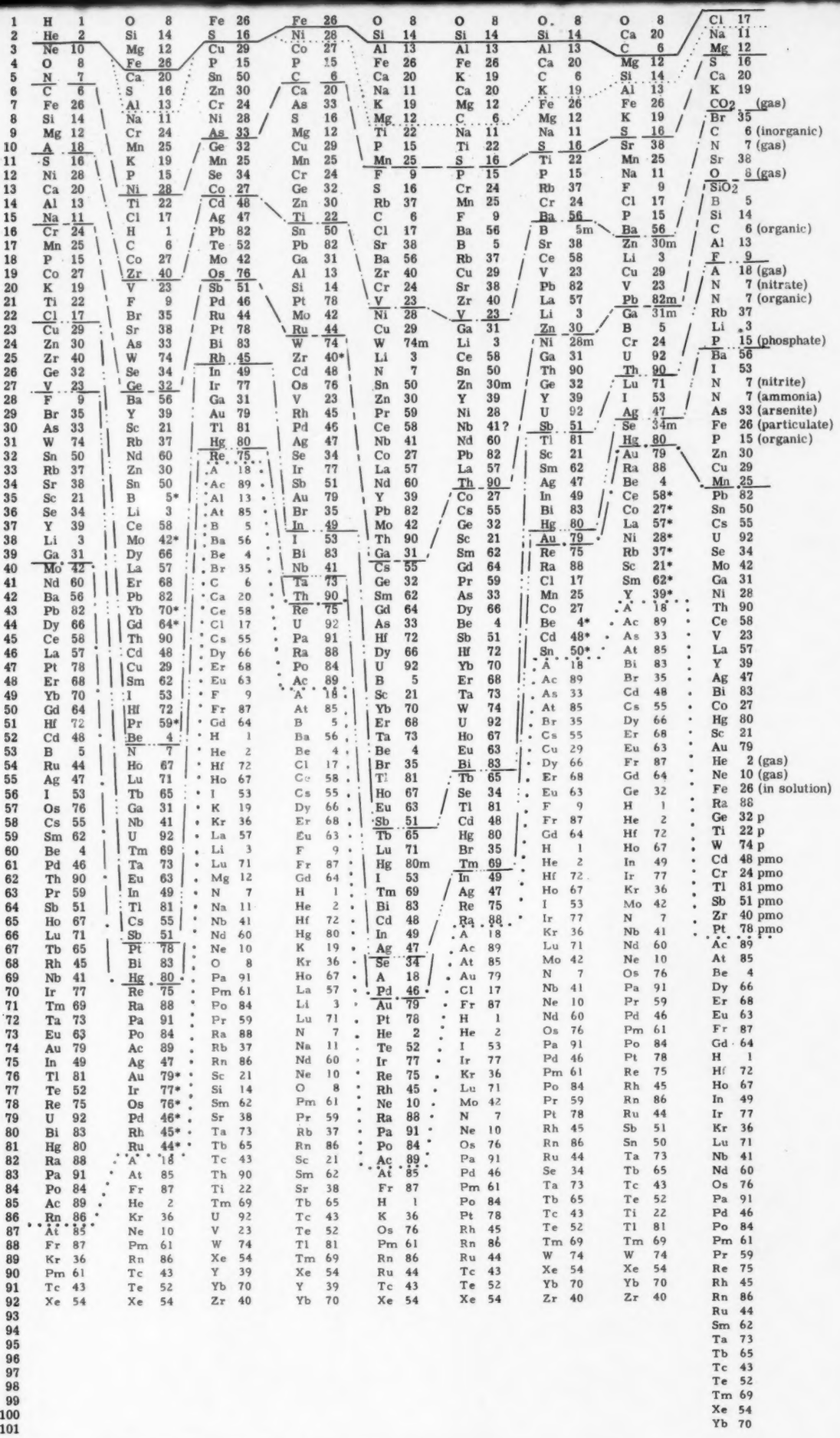
Order of Abundance of the Elements by Weight in the Geochemical Spheres

Order	Cosmos	Meteorites: Silicate	Meteorites: Sulphide	Meteorites: Iron	Igneous Rocks	Shales	Sandstones	Limestones	Ocean
1	H 1	O 8	Fe 26	Fe 26	O 8	O 8	O 8	O 8	Cl 17
2	He 2	Si 14	S 16	Ni 28	Si 14	Si 14	Si 14	Ca 20	Na 11
3	Ne 10	Mg 12	Cu 29	Co 27	Al 13	Al 13	Al 13	C 6	Mg 12
4	O 8	Fe 26	P 15	P 15	Fe 26	Fe 26	Ca 20	Mg 12	S 16
5	N 7	Ca 20	Sn 50	C 6	Ca 20	K 19	C 6	Si 14	Ca 20
6	C 6	S 16	Zn 30	Ca 20	Na 11	Ca 20	K 19	Al 13	K 19
7	Fe 26	Al 13	Cr 24	As 33	K 19	Mg 12	Fe 26	Fe 26	CO2 (gas)
8	Si 14	Na 11	Ni 28	S 16	Mg 12	C 6	Mg 12	K 19	Br 35
9	Mg 12	Cr 24	As 33	Mg 12	Ti 22	Na 11	Na 11	S 16	C 6 (inorganic)
10	A 18	Mn 25	Ge 32	Cu 29	P 15	Ti 22	S 16	Sr 38	N 7 (gas)
11	S 16	K 19	Mn 25	Mn 25	Mn 25	S 16	Ti 22	Mn 25	Sr 38
12	Ni 28	P 15	Se 34	Cr 24	F 9	P 15	P 15	Na 11	O 8 (gas)
13	Ca 20	Ni 28	Co 27	Ge 32	S 16	Cr 24	Rb 37	F 9	SiO2
14	Al 13	Ti 22	Cd 48	Zn 30	Rb 37	Mn 25	Cr 24	Cl 17	B 5
15	Na 11	Cl 17	Ag 47	Ti 22	C 6	F 9	Ba 56	P 15	Si 14
16	Cr 24	H 1	Pb 82	Sn 50	Cl 17	Ba 56	B 5m	Ba 56	C 6 (organic)
17	Mn 25	C 6	Te 52	Pb 82	Sr 38	B 5	Sr 38	Zn 30m	Al 13
18	P 15	Co 27	Mo 42	Ga 31	Ba 56	Rb 37	Ce 58	Li 3	F 9
19	Co 27	Zr 40	Os 76	Al 13	Zr 40	Cu 29	V 23	Cu 29	A 18 (gas)
20	K 19	V 23	Sb 51	Si 14	Cr 24	Sr 38	Pb 82	V 23	N 7 (nitrate)
21	Ti 22	F 9	Pd 46	Pt 78	V 23	Zr 40	La 57	Pb 82m	N 7 (organic)
22	Cl 17	Br 35	Ru 44	Mo 42	Ni 28	V 23	Li 3	Ga 31m	Rb 37
23	Cu 29	Sr 38	Pt 78	Ru 44	Cu 29	Ga 31	Zn 30	B 5	Li 3
24	Zn 30	As 33	Bi 83	W 74	W 74m	Li 3	Ni 28m	Cr 24	P 15 (phosphate)
25	Zr 40	W 74	Rh 45	Zr 40*	Li 3	Ce 58	Ga 31	U 92	Ba 56
26	Ge 32	Se 34	In 49	Cd 48	N 7	Sn 50	Th 90	Th 90	I 53
27	V 23	Ge 32	Ir 77	Os 76	Sn 50	Zn 30m	Ge 32	Lu 71	N 7 (nitrite)
28	F 9	Ba 56	Ga 31	V 23	Zn 30	Y 39	Y 39	I 53	N 7 (ammonia)
29	Br 35	Y 39	Au 79	Rh 45	Pr 59	Ni 28	U 92	Ag 47	As 33 (arsenite)
30	As 33	Sc 21	Tl 81	Pd 46	Ce 58	Nb 41?	Sb 51	Se 34m	Fe 26 (particulate)
31	W 74	Rb 37	Hg 80	Ag 47	Nb 41	Nd 60	Tl 81	Hg 80	P 15 (organic)
32	Sn 50	Nd 60	Re 75	Se 34	Co 27	Pb 82	Sc 21	Au 79	Zn 30
33	Rb 37	Zn 30	A 18	Ir 77	La 57	La 57	Sm 62	Ra 88	Cu 29
34	Sr 38	Sn 50	Ac 89	Sb 51	Nd 60	Th 90	Ag 47	Be 4	Mn 25
35	Sc 21	B 5*	Al 13	Au 79	Y 39	Co 27	In 49	Ce 58*	Pb 82
36	Se 34	Li 3	At 85	Br 35	Pb 82	Cs 55	Bi 83	Co 27*	Sn 50
37	Y 39	Ce 58	B 5	In 49	Mo 42	Ge 32	Hg 80	La 57*	Cs 55
38	Li 3	Mo 42*	Ba 56	I 53	Th 90	Sc 21	Au 79	Ni 28*	U 92
39	Ga 31	Dy 66	Be 4	Bi 83	Ga 31	Sm 62	Re 75	Rb 37*	Se 34
40	Mo 42	La 57	Br 35	Nb 41	Cs 55	Gd 64	Ra 88	Sc 21*	Mo 42
41	Nd 60	Er 68	C 6	Ta 73	Ge 32	Pr 59	Cl 17	Sm 62*	Ga 31
42	Ba 56	Pb 82	Ca 20	Th 90	Sm 62	As 33	Mn 25	Y 39*	Ni 28
43	Pb 82	Yb 70*	Ce 58	Re 75	Gd 64	Dy 66	Co 27	A 18	Th 90
44	Dy 66	Gd 64*	Cl 17	U 92	As 33	Be 4	Be 4*	Ac 89	Ce 58
45	Ce 58	Th 90	Cs 55	Pa 91	Hf 72	Sb 51	Cd 48*	As 33	V 23
46	La 57	Cd 48	Dy 66	Ra 88	Dy 66	Hf 72	Sn 50*	At 85	La 57
47	Pt 78	Cu 29	Er 68	Po 84	U 92	Yb 70	A 18	Bi 83	Y 39
48	Er 68	Sm 62	Eu 63	Ac 89	B 5	Er 68	Ac 89	Br 35	Ag 47
49	Yb 70	I 53	F 9	A 18	Sc 21	Ta 73	As 33	Cd 48	Bi 83
50	Gd 64	Hf 72	Fr 87	At 85	Yb 70	W 74	At 85	Cs 55	Co 27
51	Hf 72	Pr 59*	Gd 64	B 5	Er 68	U 92	Br 35	Dy 66	Hg 80
52	Cd 48	Be 4	H 1	Ba 56	Ta 73	Ho 67	Cs 55	Er 68	Sc 21
53	B 5	N 7	He 2	Be 4	Be 4	Eu 63	Cu 29	Eu 63	Au 79
54	Ru 44	Ho 67	Hf 72	Cl 17	Br 35	Bi 83	Dy 66	Fr 87	He 2 (gas)
55	Ag 47	Lu 71	Ho 67	Ce 58	Tl 81	Tb 65	Er 68	Gd 64	Ne 10 (gas)
56	I 53	Tb 65	I 53	Cs 55	Ho 67	Se 34	Eu 63	Ge 32	Fe 26 (in solution)
57	Os 76	Ga 31	K 19	Dy 66	Eu 63	Tl 81	F 9	H 1	Ra 88
58	Cs 55	Nb 41	Kr 36	Er 68	Sb 51	Cd 48	Fr 87	He 2	Ge 32 p
59	Sm 62	U 92	La 57	Eu 63	Tb 65	Hg 80	Gd 64	Hf 72	Tl 22 p
60	Be 4	Tm 69	Li 3	F 9	Lu 71	Br 35	H 1	Ho 67	W 74 p
61	Pd 46	Ta 73	Lu 71	Fr 87	Hg 80m	Tm 69	He 2	In 49	Cd 48 pmo
62	Th 90	Eu 63	Mg 12	Gd 64	I 53	In 49	Hf 72	Ir 77	Cr 24 pmo
63	Pr 59	In 49	N 7	H 1	Tm 69	Ag 47	Ho 67	Kr 36	Tl 81 pmo
64	Sb 51	Tl 81	Na 11	He 2	Bi 83	Re 75	I 53	Mo 42	Sb 51 pmo
65	Ho 67	Cs 55	Nb 41	Hf 72	Cd 48	Ra 88	Ir 77	N 7	Zr 40 pmo
66	Lu 71	Sb 51	Nd 60	Hg 80	In 49	A 18	Kr 36	Nb 41	Pt 78 pmo
67	Tb 65	Pt 78	Ne 10	K 19	Ag 47	Ac 89	Lu 71	Nd 60	Ac 89
68	Rh 45	Bi 83	O 8	Kr 36	Se 34	At 85	Mo 42	Ne 10	At 85
69	Nb 41	Hg 80	Pa 91	Ho 67	A 18	Au 79	N 7	Os 76	Be 4
70	Ir 77	Re 75	Pm 61	La 57	Pd 46	Cl 17	Nb 41	Pa 91	Dy 66
71	Tm 69	Ra 88	Po 84	Li 3	Au 79	Fr 87	Ne 10	Pr 59	Er 68
72	Ta 73	Pa 91	Pr 59	Lu 71	Pt 78	H 1	Nd 60	Pd 46	Eu 63
73	Eu 63	Po 84	Ra 88	N 7	He 2	He 2	Os 76	Pm 61	Fr 87
74	Au 79	Ac 89	Rb 37	Na 11	Te 52	I 53	Pa 91	Po 84	Gd 64
75	In 49	Ag 47	Rn 86	Nd 60	Ir 77	Ir 77	Pd 46	Pt 78	H 1
76	Tl 81	Au 79*	Sc 21	Ne 10	Re 75	Kr 36	Pm 61	Re 75	Hf 72
77	Te 52	Ir 77*	Si 14	O 8	Rh 45	Lu 71	Po 84	Rh 45	Ho 67
78	Re 75	Os 76*	Sm 62	Pm 61	Ne 10	Mo 42	Pr 59	Rn 86	In 49
79	U 92	Pd 46*	Sr 38	Pr 59	Ra 88	N 7	Pt 78	Ru 44	Ir 77
80	Bi 83	Rh 45*	Ta 73	Rb 37	Pa 91	Ne 10	Rh 45	Sb 51	Kr 36
81	Hg 80	Ru 44*	Tb 65	Rn 86	Po 84	Os 76	Rn 86	Sn 50	Lu 71
82	Ra 88	A 18	Tc 43	Sc 21	Ac 89	Pa 91	Ru 44	Ta 73	Nb 41
83	Pa 91	At 85	Th 90	Sm 62	At 85	Pd 46	Se 34	Tb 65	Nd 60
84	Po 84	Fr 87	Ti 22	Sr 38	Fr 87	Pm 61	Ta 73	Tc 43	Os 76
85	Ac 89	He 2	Tm 69	Tb 65	H 1	Po 84	Tb 65	Te 52	Pa 91
86	Rn 86	Kr 36	U 92	Tc 43	K 36	Pt 78	Tc 43	Ti 22	Pd 46
87	At 85	Ne 10	V 23	Te 52	Os 76	Rh 45	Te 52	Tl 81	Po 84
88	Fr 87	Pm 61	W 74	Tl 81	Pm 61	Rn 86	Tm 69	Tm 69	Pm 61
89	Kr 36	Rn 86	Xe 54	Tm 69	Rn 86	Ru 44	W 74	W 74	Pr 59
90	Pm 61	Tc 43	Y 39	Xe 54	Ru 44	Tc 43	Xe 54	Xe 54	Re 75
91	Tc 43	Te 52	Yb 70	Y 39	Tc 43	Te 52	Yb 70	Yb 70	Rh 45
92	Xe 54	Xe 54	Zr 40	Yb 70	Xe 54	Xe 54	Zr 40	Zr 40	Rn 86
93									Ru 44
94									Sm 62
95									Ta 73
96									Tb 65
97									Tc 43
98									Te 52
99									Tm 69
100									Xe 54
101									Yb 70

* value equal to preceding and succeeding element (equals 0 if at end of list.)
m maximum value
p present
pmo present in marine organisms

(Oceanic abundances arranged according to maximum concentration)

——— 100,000 g/ton (p.p.m.)
····· 10,000 g/ton
— — 1,000 g/ton
·—·— 100 g/ton
——·—— 10 g/ton
——··—— 1.0 g/ton



* value equal to preceding and succeeding element (equals 0 if at end of list.)

m maximum value

p present

pmo present in marine organisms

(Oceanic abundances arranged according to maximum concentration)

——— 100,000 g/ton (p.p.m.)

····· 10,000 g/ton

— — 1,000 g/ton

·—·—· 100 g/ton

——·—— 10 g/ton

——··—— 1.0 g/ton

——···—— 0.1 g/ton

——·—·—— 0.01 g/ton

·· ····· 0.00 g/ton below which are the rest of the 92 elements arranged alphabetically

Numbers following elements are atomic numbers.

Elements in lightface type are those for which there are no data. The degree of accuracy of the data does not warrant comparisons of abundance values for adjacent elements present in concentrations below 100 grams per ton.

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GRENVILLE SERIES IN THE NORTHWEST ADIRONDACK MOUNTAINS, NEW YORK

PART I: GENERAL FEATURES OF THE GRENVILLE SERIES

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ABSTRACT

The Precambrian metasediments of the Grenville series, or rocks with kindred features, have been identified from Georgian Bay, southeastern Ontario, northeastward as far as Labrador and southward into the Adirondack Mountains of New York, the Green Mountains of Vermont, and the Precambrian highlands of northern New Jersey, southern New York, and southeastern Pennsylvania. This region also includes a distinctive series of intrusive rocks ranging from anorthosite to granite and may be referred to as the Grenville subprovince. The thickness of the Grenville series, or its inferred equivalents, is the subject of much speculation. Its maximum thickness is probably in southeastern Ontario and in the northwest Adirondacks, where the exposed sequences probably total about 20,000 feet. Eastward, in the vicinity of the type locality at Grenville village, Argenteuil County, Quebec, the exposed Grenville series may be only 5000 or at most 10,000 feet thick; northeast of the type locality, near Shawinigan Falls, the known Grenville series may be less than 5000 feet thick. Few data are available on thickness of the Grenville series in other parts of the subprovince.

Most of the Grenville series is moderately to highly deformed, and injected. In the Adirondacks and in parts of Ontario and Quebec, the anorthosites appear to be the oldest rocks intrusive into the Grenville series, followed successively by gabbros, diorites, syenites, and a granitic complex. In some parts of western Quebec and elsewhere, a post-Grenville pre-anorthosite epoch of granitic intrusion may have occurred. Throughout the subprovince, however, an igneous series of anorthosite, gabbro, syenite, and granite appear to be genetically related, either as successive fractions from a deep-seated magma source or as differentiates evolved from a magma of intermediate composition during its penetration of the Grenville series.

All the intrusive magmas have interacted with the Grenville series to produce hybrid rocks and skarns. The widespread chemical alterations and dynamothermal metamorphism of the Grenville series largely are related, however, to the emplacement of granites which post-date both anorthosite and gabbro. Some granitic masses exhibit well-defined contact-metamorphic aureoles. Elsewhere areas of granite are not clearly separable from granitized sediment and migmatite. Nests and irregular masses of skarn and contact minerals also are interspersed with relatively unaltered metasediment. Paragneisses are injected *lit-par-lit* and partially granitized. Some marbles are converted into hornblende-andesine amphibolites, and others, through interaction with granitic and aqueous fluids, are altered to or replaced by pyrite, magnetite, diopside, tremolite, phlogopite, scapolite, serpentine, talc, and many other minerals.

A gross relationship exists between the most thoroughly deformed and sheared-out metasediments and areas of abundant igneous rock. Two of the best-documented examples of regional variations in degree of dynamothermal metamorphism that can be related to large igneous massifs are those in the Haliburton-Bancroft area of Ontario and in the Adirondack Mountains of New York. Even those metasediments farthest from igneous massifs are completely recrystallized and reconstituted, however, commonly into the amphibolite or a higher-rank metamorphic facies. In the clastic rocks almandite, biotite, and either oligoclase or potash feldspar are dominant minerals, and many segments of these rocks contain appreciable sillimanite. Carbonate rocks are dominated by diopside, tremolite, hornblende, and andesine with occasional nests of wollastonite formed along and near the contacts of various intrusive rocks.

Most of the Grenville series, and the Grenville type metasediments, are highly folded, commonly along northeast-trending axes. Marked divergences from this regional trend are especially prominent in the vicinity of large anorthosite and granitic massifs. At least one region of more open folds and moderate de-

bond. Transitions exist, and the "pure bond type" is the exception, not the rule.

Phase 2—Partition of elements during crystallization of magma. Elements now are partitioned by the "sieve" size of the crystal through which the ions may move. Ionic charge and radius, electronegativity, and concentration are here the governing factors. Enthalpy is lower than in Phase 1.

Phase 3—Partition of elements during weathering under low enthalpy conditions. Ionic potential and electronegativity are important factors in this phase. Correns (1949, p. 208) believes that crystal surfaces possess unsatisfied valences which form loci of reaction with water molecules. Hydration and hydrolysis result in the removal of cations such as K^{+1}, Ca^{+2}, and Mg^{+2}, while the oxygen anions in the crystal lattice may in part be replaced by hydroxyl ions. Al^{+3} and Si^{+4} attract OH^{-1} ions strongly. These ions are in ionic solution when first set free, but the ions tend to aggregate and form clusters of colloidal size. Initially the colloidal masses may be amorphous, but orientation into definite crystal lattices occurs on aging, and clay minerals are thus formed. Goldschmidt (1937b, p. 665–666) made the analogy that nature analyses a rock during weathering in the same manner as an analytical chemist does (Fig. 1).

Phase 4—Organisms also partition elements in accordance with their needs ("the nutrient line") or their peculiarities. Why, for instance, oysters should concentrate copper will perhaps forever remain an oyster's secret.

The above four phases and their relation to the fundamental bond types are shown in Table 1. Partitions in Phase 1 and, to a lesser extent, in Phase 2 are governed by the thermodynamics and rate processes of reactions under high temperature with the important parameters of high pressure and variable gravity (Ramberg, 1944; 1945; Brewer, 1951). Our relatively poor knowledge of Phases 1 and 2 is offset by the greater complexity of reactions in Phases 3 and 4.

"Considering the earth as a whole and disregarding any substantial and energetic communication with the universe, it is evident that the net result of all geological processes is a more stable over-all situation, with an increase in the entropy and a corresponding decrease in the free energy . . . [However] with smaller or greater confined parts of the earth's crust . . . energetic and substantial communication between the complex considered and the surroundings may provide changes in entropy and free energy in either direction in the complex under consideration. (Ramberg, 1952, p. 5).

All the elements have been arranged in order of abundance in Table 2. In the cosmos H and He total 98.5 per cent by weight; in the silicate phase of meteorites O, Si, Mg, and Fe total more than 93 per cent; in the sulphide phase Fe and S total 95.4 per cent; in the iron phase Fe and Ni total 99.4 per cent; and in igneous rocks O, Si, Al, Fe, Ca, Na, K, and Mg total 98.7 per cent. The columns have been divided at 100,000, 10,000, 1,000, 100, 10, 1.0, 0.1, and 0.01 parts per million or g/ton. Elements and compounds in the ocean are arranged according to maximum concentrations.

It is hoped that the information presented in this chart makes all available data readily accessible to workers in geochemistry and allied fields. Periodic variations in thermodynamic properties, density (Lebedev, 1948, p. 517), ionic potential (Cartledge, 1928, p. 2859), ionization potential (Pauling, 1945, p. 65), and ionic and atomic volumes (Goldschmidt, 1926, p. 54–55) may be graphed for further information. It is also of interest to compare costs with abundances. The evidence for the rule of Oddo and Harkins (Harkins, 1917, p. 858; 1931, p. 1286) can likewise be tested in cosmic abundances, while that of crustal differentiation is reflected in the terrestrial abundances.

Yet the chart is far from complete and will need to be brought up to date as more data accumulate. To quote Fairbairn *et al.* (1951, p. 71), "published abundance values for minor elements in the earth's crust need critical review since they are based on work in a few laboratories only, with no interlaboratory standardization."

It is further hoped that progress in geochemistry will be such that this geochemical table of the elements for 1953 will rapidly become obsolete.

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An asterisk indicates that the article is included in Ingerson (1953). Nonradiogenic isotope data have been taken from these publications.

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GRENVILLE SERIES IN THE NORTHWEST ADIRONDACK MOUNTAINS, NEW YORK

PART I: GENERAL FEATURES OF THE GRENVILLE SERIES

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ABSTRACT

The Precambrian metasediments of the Grenville series, or rocks with kindred features, have been identified from Georgian Bay, southeastern Ontario, northeastward as far as Labrador and southward into the Adirondack Mountains of New York, the Green Mountains of Vermont, and the Precambrian highlands of northern New Jersey, southern New York, and southeastern Pennsylvania. This region also includes a distinctive series of intrusive rocks ranging from anorthosite to granite and may be referred to as the Grenville subprovince. The thickness of the Grenville series, or its inferred equivalents, is the subject of much speculation. Its maximum thickness is probably in southeastern Ontario and in the northwest Adirondacks, where the exposed sequences probably total about 20,000 feet. Eastward, in the vicinity of the type locality at Grenville village, Argenteuil County, Quebec, the exposed Grenville series may be only 5000 or at most 10,000 feet thick; northeast of the type locality, near Shawinigan Falls, the known Grenville series may be less than 5000 feet thick. Few data are available on thickness of the Grenville series in other parts of the subprovince.

Most of the Grenville series is moderately to highly deformed, and injected. In the Adirondacks and in parts of Ontario and Quebec, the anorthosites appear to be the oldest rocks intrusive into the Grenville series, followed successively by gabbros, diorites, syenites, and a granitic complex. In some parts of western Quebec and elsewhere, a post-Grenville pre-anorthosite epoch of granitic intrusion may have occurred. Throughout the subprovince, however, an igneous series of anorthosite, gabbro, syenite, and granite appear to be genetically related, either as successive fractions from a deep-seated magma source or as differentiates evolved from a magma of intermediate composition during its penetration of the Grenville series.

All the intrusive magmas have interacted with the Grenville series to produce hybrid rocks and skarns. The widespread chemical alterations and dynamothermal metamorphism of the Grenville series largely are related, however, to the emplacement of granites which post-date both anorthosite and gabbro. Some granitic masses exhibit well-defined contact-metamorphic aureoles. Elsewhere areas of granite are not clearly separable from granitized sediment and migmatite. Nests and irregular masses of skarn and contact minerals also are interspersed with relatively unaltered metasediment. Paragneisses are injected *lit-par-lit* and partially granitized. Some marbles are converted into hornblende-andesine amphibolites, and others, through interaction with granitic and aqueous fluids, are altered to or replaced by pyrite, magnetite, diopside, tremolite, phlogopite, scapolite, serpentine, talc, and many other minerals.

A gross relationship exists between the most thoroughly deformed and sheared-out metasediments and areas of abundant igneous rock. Two of the best-documented examples of regional variations in degree of dynamothermal metamorphism that can be related to large igneous massifs are those in the Haliburton-Bancroft area of Ontario and in the Adirondack Mountains of New York. Even those metasediments farthest from igneous massifs are completely recrystallized and reconstituted, however, commonly into the amphibolite or a higher-rank metamorphic facies. In the clastic rocks almandite, biotite, and either oligoclase or potash feldspar are dominant minerals, and many segments of these rocks contain appreciable sillimanite. Carbonate rocks are dominated by diopside, tremolite, hornblende, and andesine with occasional nests of wollastonite formed along and near the contacts of various intrusive rocks.

Most of the Grenville series, and the Grenville type metasediments, are highly folded, commonly along northeast-trending axes. Marked divergences from this regional trend are especially prominent in the vicinity of large anorthosite and granitic massifs. At least one region of more open folds and moderate de-

formation of the Grenville series appears between the Morin anorthosite mass and the Saguenay River In the areas of more profound deformation, all the metasediments have yielded not only by cataclassis but by profound solid flow. Flowage features are especially prominent, however, in the carbonate zones. Some of these carbonate units have pulled or flowed apart in areas of constriction or stretching, commonly along the short flanks of major folds, and are enormously thickened elsewhere, usually in apical areas of folds. Differences in rate or amount of flow in different lithologic layers have induced markedly disharmonic folded forms, pseudo-unconformities, and tectonic breccias. In general, however, rock motions have followed the sedimentary patterns, and the gross patterns of flow surfaces are rudely accordant with relict bedding.

The dominant metasedimentary rock types within the Grenville series are marbles, quartzites, amphibolites, and biotitic, garnetiferous, and sillimanitic paragneisses. Siliceous and magnesian marbles are especially typical along and west of the Ottawa River, in southeastern Ontario, in the Adirondacks, Vermont, and in the highlands of northern New Jersey. Eastward beyond Lake St. John (St. Jean), Quebec, the correlation of the "Grenville series" is based largely upon amphibolites, quartzites, and "paragneisses" which include both biotitic and hornblendic quartz-feldspar gneisses.

The southwesterly, carbonate-rich facies are in large part unequivocally correlative with the type section described by Logan near Grenville village, Quebec. In the Adirondacks and northwest toward the Haliburton-Bancroft area of Ontario, this segment of the Grenville series includes at least two magnesian carbonate units, each a mile or more thick before metamorphism. These appear to thin northeastward from the type locality and southeast across the Adirondacks. In northern New Jersey, however, the Grenville-type marble of the Franklin formation appears to be at least 2000 feet thick.

The magnesia content of the marbles may be in part primary or syngenetic, although in the Haliburton-Bancroft area of Ontario, in parts of southwestern Quebec, and in northern New Jersey, dolomitization of an initially calcitic marble is reportedly related to the intrusion of igneous rocks. In the Northwest Adirondacks, some of the oldest marble layers are dolomite. Some of the magnesia in these has been abstracted during metamorphism, moved appreciable distances, and concentrated in deposits of tremolite, anthophyllite, serpentine, and talc.

Much of the silica in the marbles of the Grenville series undoubtedly is primary although probably a fourth to a half of the present total is introduced. Other substances in the marble which may be at least in part sedimentary include pyrite, graphite, gypsum, anhydrite, halite, and members of the paraffin series. In the northwest Adirondacks, anhydrite and methane occur in well-defined interbeds, and the existing data favor a sedimentary origin for these components.

Quartz-feldspar paragneisses, either appreciably sillimanitic and garnetiferous or highly biotitic, appear almost everywhere that Grenville-like rocks are found in the subprovince. In areas of appreciable marble paragneisses commonly rank second to marbles in abundance. In the northwest Adirondacks, for example, the largest gneissic unit is about 3000 feet thick. Northeastward, from the type locality, as the marbles thin or disappear, paragneisses tend to dominate the Grenville series. Most of the thicker gneissic units are either quartz-sillimanite-feldspar or quartz-biotite-feldspar types, in general much injected by granite. In the Adirondacks, in parts of southeastern Ontario, east of the Saguenay River in Quebec, and in New Jersey, the least-altered gneisses have a bulk composition approaching that of many graywackes, dacitic tuffs, or sodic shales. Along the Ottawa River, however, and in parts of southwestern Quebec, the paragneisses seem to approach more closely the composition of Clarke's average shale.

Quartzites appear as narrow interlayers and as zones throughout the known and inferred extent of the Grenville series. Among the quartzites are almost pure quartz types, as well as types intermediate between quartzite and gneiss, marble, and amphibolite. Many of the siliceous interlayers, especially in the marble, are either laminated or lenticular to nodular, and some if not most of these rocks presumably were deposited as microcrystalline cherts or novaculite-like types.

Amphibolites also are ubiquitous. Most are hornblende-andesine rocks with associated augite, diopside, apatite, calcite, and other minerals. Many amphibolites clearly are derived from gabbroic and basaltic rocks, and others as surely represent skarnlike replacements of marbles. In addition, numerous amphibolites are inferred to represent reconstituted tuffs and marly interbeds. In many areas of the Grenville subprovince, however, neither the rock types transitional between the parent and the resulting amphibolite, nor the parent rock are preserved, and the origin of the evolved amphibolite cannot be stated with any assurance. An obvious corollary is that problems of stratigraphic and structural synthesis are greatly complicated where the section includes an appreciable thickness of enigmatic amphibolites.

The characteristic assemblage of marble, paragneiss, and quartzites which constitutes the typical Grenville series has been described repeatedly as representing "normal marine limestones, shales and sandstones

of the well sorted type." Other workers in the same or near-by areas have described interlayers and zones in the Grenville series as arkoses, tuffs, and graywackes. Some of the same parts of the Grenville series also are depicted as either including, or being intimately associated with, conglomerates, pillow lavas, and iron formations. The implication is clearly that of a highly anomalous association of rock types which do not fit into contemporary, genetic classifications, or readily inferred environments, of sediments.

Many seeming contradictions disappear, however, if all citations of original sedimentary facies are excluded from discussions except those that are reasonably established in origin and recognizable as probable parts of the Grenville series. Some real enigmas remain, nevertheless, which cannot be ascribed to inaccurate identifications or uncertain correlations.

All the examples of sedimentary iron formation ascribed to the Grenville series appear to be most hypothetical, if not spurious. Arkoses are equally suspect, especially in the carbonate-rich segments of the series. Feldspathic quartzites or paragneisses are common enough as integral parts of the sequence, but instead of representing arkoses these are more reasonably interpreted as secondarily feldspathized quartzites or as reconstituted, illitic sandstones.

The term graywacke is applied widely and loosely in descriptions of the Grenville series to many gray to dark-green gneissic and schistose interlayers which must have had divergent origins. In Hastings County, Ontario, however, and southwestward along this margin of the Grenville subprovince, unequivocal conglomerates, pillow lavas, and probably agglomerates either underlie, or overlie, and possibly form interlayers in carbonate-rich segments of the Grenville series. These suggest that the Grenville series of this area was deposited on an unstable area of the earth's crust in which positive as well as markedly negative segments evolved during sedimentation. Graywackes may have formed although documentary data on their existence are lacking. Eastward from this area, the conglomerates and lavas disappear, although part of this region includes not only marble and quartzites, but the paragneisses with the composition and many lithologic features of graywackes, tuffs, or aberrantly sodic shales. There are in addition the paragneisses which may have evolved from typical shales. The extreme thickness of the section, the abundance of siliceous magnesian carbonate rocks, and the probable occurrence of sedimentary anhydrite and halite suggest that this segment of the Grenville series was deposited in a large persistently negative basin, either periodically or locally cut off from the open ocean.

The basin appears to have extended from Lake Nipissing southeastward across the Adirondacks, possibly into New Jersey. Its northeast margin must have been well beyond the type locality in western Quebec.

The environment of deposition of the Grenville-type sediments northeast of the Saguenay will remain most speculative until much more is known of the composition and geologic features of the metasediments. They undoubtedly are derived from clastic rocks, especially sandstones and finer fractions. Marbles are uncommon, or relatively unimportant, although some of the amphibolites could represent skarnlike replacements of carbonate zones. Whether arkoses or graywackes are represented also is of particular interest in proposing an environment of deposition. The numerous reports of abundant sodic oligoclase in many of the paragneisses suggest that some clastic zones could have been graywackes, or tuffs of intermediate composition, or sodic shales.

Throughout most of the Grenville subprovince, the Grenville series are the oldest decipherable rocks. Analyses of lead and uranium in granitic and pegmatitic minerals, and of helium in magnetite ores in the Grenville subprovince give ages ranging from 1.0×10^9 to 1.3×10^9 years. All these minerals were emplaced at about the culmination of metamorphism of the Grenville series. Earlier epochs as yet undated include the premetamorphic intrusions of anorthosites, gabbros, and syenites and the period of Grenville sedimentation. Presumably the inception of this sedimentation occurred some 1.2×10^9 or more years ago.

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Introduction

The Precambrian metasedimentary rocks referred to the Grenville series in the northwest Adirondacks, New York, have interested geologists for several generations. Each generation has been impressed by the apparently great age and volume of these sediments, the striking carbonate-rich facies, the obvious and spectacular changes wrought by superimposed igneous and metamorphic processes, and by the scientifically exciting and economically important mineral deposits.

These features, combined with ease of access to the region and the wealth of rock exposures therein, have provoked an abnormally heavy traffic of geologists and students. In 1945 the writers became a part of that group and during the succeeding years have found their interest in the Grenville series intensified. They now feel sufficiently well acquainted with some of the earth problems posed by these rocks to attempt their discussion.

Most of the problems raised in conjunction with work in the northwest Adirondack segment of the Grenville series are best considered, however, in a broader, regional context. Accordingly, Part I summarizes some of the data and ideas bearing on the Grenville series throughout its known and inferred extent.

Succeeding papers—Parts II, III, etc.,—will deal specifically with the writers' studies of the Grenville series in the northwest Adirondacks and will utilize this discussion as a background and frame of reference.

Acknowledgments

The following discussion has been made possible by, and draws heavily upon, the work of many others in the Grenville subprovince and elsewhere. It is a pleasure to acknowledge our indebtedness to colleagues in both the United States and Canada.

The papers and friendly counsel of J. S. Brown, A. F. Buddington, Norman H. Donald, B. F. Leonard, and James Gilluly have proved especially invaluable as a source of data, ideas, and inspiration. Our Adirondack studies are sponsored by the U. S. Department of Interior, Geological Survey, and invaluable help continually is received from members of this organization.

Distribution of Grenville Type Sediments

A century has elapsed since Logan mapped and described a sequence of Precambrian marble, quartzite, and gneisses near Grenville village, Argenteul County, Quebec, as the "Grenville belt" (1865). Since then very similar Precambrian marbles, with associated quartzites, gneisses, schists, and amphibolites, have been traced into or found in adjacent areas and at most other points of geologic study within a large area of southeastern Canada and northeastern United States. These and associated rocks have been correlated—with varying degrees of conviction and enthusiasm—with those near Grenville, Quebec, and described as the Grenville series. The region defined by these occurrences and, to some minds, by the distribution of a seemingly related series of distinctive igneous rocks has been described as the Grenville subprovince. Its extent as commonly defined is shown on Figure 1. (*See also* Wilson, 1925; 1939; Gill, 1948; and Tectonic Map of Canada, 1951.) On Figure 1 an attempt is made to show, in most of the places where data are available, the distribution and relative im-

FIGURE 1. MAP OF THE MORE EXPOSED PARTS OF THE GRENVILLE SUBPROVINCE OF THE CANADIAN SHIELD

Dashed lines indicate lithologic trends of the metasedimentary rocks at some of the better-known localities. The relative importance of, respectively, amphibolite, conglomerate, marble, paragneiss, quartzite, and volcanics in any area is indicated by the size of the letters A, C, M, P, Q, and V. Compiled largely from reports and maps of the Geological Survey of Canada, the Ontario and Quebec Bureau of Mines, the Tectonic Map of Canada, the Reports of the New York State Museum, and the authors' field studies.

portance of the major rock types of the Grenville series. The data are compiled from geological maps and reports of the Quebec and Ontario Departments of Mines, the Canadian Geological Survey, the New York State Museum, the Tectonic Map of Canada published by the Geological Society of Canada, and from the authors' field studies.

In Canada, for example, metasedimentary rocks referred to the Grenville series appear at intervals from Georgian Bay, on the eastern shore of Lake Huron, eastward and northeastward at least as far as Labrador, and southward to the St. Lawrence River. South of the St. Lawrence, the carbonate-rich Precambrian metasedimentary rocks of the Adirondacks have been referred to the Grenville series almost since the inception of the term. Moreover, imaginative or zealous protagonists of long-range correlation readily saw Grenville affinities in the Precambrian carbonate and clastic metasediments of the Green Mountains, Vermont, and in the highlands of New Jersey, Eastern Pennsylvania, and southern New York.

Although these more southeasterly outliers of Grenville type rocks are rarely included in the Grenville subprovince, the data presented here indicate they are in many respects more nearly kindred to the Grenville series of the type locality in Argenteul County, Quebec, than are many inferred extensions of the Grenville series in the eastern parts of the "subprovince."

Thickness

Early workers suggested that the Grenville series was 10 to 20 miles thick west of the type locality, in and near the Haliburton-Bancroft area, Ontario (Adams and Barlow, 1910, p. 35; Vennor, 1878, p. 229–300). Subsequent studies have revised these estimates markedly downward. Osborne (1936a, p. 15, 16; 1936b, p. 202) suggests that at the type locality near Grenville Village, Hastings County, Quebec, the Grenville series is somewhere between 5000 and 10,000 feet thick, and in the Haliburton-Bancroft area "is probably less than 20,000 feet" (1936b, p. 202), or possibly "only a few thousand feet thick" (Osborne, 1931, p. 27–28). However, the rocks of these areas are complexly deformed, the stratigraphic sequence is in doubt, and neither base nor top of the series is well defined. Presumably the Grenville series thins eastward in Canada, for at and near Shawinigan Falls, Quebec, Osborne (1936c, p. 410) has estimated the exposed Grenville series —from an inferred base of orthoamphibolite— at 3000 to 5000 feet thick.

The exposed Grenville series in the northwest Adirondacks, some 100 miles south of the type locality, probably is at least 15,000 feet thick. Brown (1936, p. 236–239) has estimated that several major units in the Balmat-Edwards district, New York, have an aggregate thickness of about 16,000 feet, but this could involve the repetition of one gneissic unit, and clearly omits from consideration two major marble units to the northwest. Cushing's estimate of 20,000 feet (1925, p. 17) for the exposed Grenville series in the northwest Adirondacks may be close although his postulated stratigraphic sequence is incorrect. Buddington has suggested a total thickness of about 11,000 feet for three of the five major units recognizable, which seems to be very close. The writers' studies suggest that the thickness of the exposed Grenville series in the northwest Adirondacks is approximately 16,000 feet, and it must have approached or possibly exceeded 20,000 feet before metamorphism (Table 1, Part II). In this area of the Adirondacks, no rocks or relations suggestive of a base or top to the series are known, nor is there an obvious break in the series.[1]

The above data pertain only to the carbonate-bearing parts of the Grenville series in the western and southwestern parts of the subprovince. They suggest that in this region the thickest exposed sections occur from the Adirondacks northwest toward Bancroft, Ontario, and east into the type locality, beyond which the Grenville series may thin appreciably in Quebec. Interestingly enough, this thinning—if such it is—coincides with a decrease in total thickness and proportion of carbonate rocks in the Grenville series. These relations are discussed more fully in the section on Marble.

East and northeast of the Saguenay River

[1] A discussion of the stratigraphy and structure of the Grenville series in the northwest Adirondacks constitutes Part IV of these studies.

in the northeast part of the subprovince, little is known concerning the thickness of rocks referred to the Grenville series.

Metamorphism

Metamorphic features genetically related to the intrusion of igneous rocks into the Grenville series are apparent throughout the subprovince. None of these sedimentary rocks have escaped this metamorphism although some striking differences exist in the degree, kind, and scale of the changes. In general the major and widespread chemical alterations of the Grenville series or inferred Grenville type sediments are induced by granitic magmas and widely traveled fluids therefrom, although scattered pyrometasomatic deposits are formed clearly by mafic intrusives. The metamorphism almost invariably has involved metasomatism on a large scale, and of markedly nonuniform pattern.

Most changes involving recrystallization, reconstitution, and deformation of the metasediments are induced through a subtle interplay of intrusive phenomena and regional dynamothermal metamorphism. In several of the regions where large igneous massifs intrude metasediments, a gross correlation exists between proximity to the massif and the degree of physico-chemical alteration of the metasediments.

The Haliburton-Bancroft area, Ontario (Adams and Barlow, 1910), the Lachute area, Quebec (Osborne, 1936a, p. 15–16), the Adirondacks (Buddington, 1939), and the highland area of northern New Jersey (A. F. Buddington, written communication; Sims, 1953; Sims and Leonard, 1952) are outstanding examples of this type. A well-defined correlation between intensity of metamorphism and abundance of intrusive igneous rocks also appears to pertain in the region between Madoc and points farther east-northeast and north in southeastern Ontario (Wilson, 1925, p. 394–395; Harding, 1951, p. 11).

Associated Igneous Rocks

All major occurrences of the Grenville series, or of Grenville type sediments are injected and permeated by magma or by constituents readily ascribed to a magmatic source. Commonly, several distinctive igneous rock types are found in close association, seemingly as components of a genetically related, magmatic series. Where these igneous complexes are most extensively developed, they include anorthosites, gabbros, diorites, shonkonitic or charnokitic syenites, quartz syenites, and granites. (*See, for example*, Buddington, 1939; 1948; Osborne, 1936c; Retty, 1944; Wilson, 1925.) All these associated intrusives are younger than the Grenville series but were emplaced in periods preceding, during, and seemingly in the waning stages of regional metamorphism.[2]

The close association of some or all of these magma types with the Grenville series in many areas, and their distinctive features, as compared with dominant magma types in the Timiskaming and Huronian type metasediments, has been recognized for many years. Logan grouped anorthosites, syenites, and granites with the Grenville series as the "Laurentian system" (1865). Wilson's definition of the Grenville subprovince (1925, p. 389) also refers "the bedrock formations" to a "basal complex" in which he includes the Grenville series and a "related series of igneous intrusives—peridotite, gabbro, diorite, shonkonite, etc. . . . ." Many geologists working in the Grenville series since have concluded that these igneous rocks, like the metasedimentary units, are manifestations of the crustal mechanics distinctive to the evolution of the Grenville subprovince.

In recent years, most workers in widely separated areas have concluded that the igneous types were emplaced in order of increasing acidity, with anorthosites and gabbros as the oldest post-Grenville intrusives. Most earlier workers, however, as well as some contemporary students have concluded that the oldest post-Grenville intrusives are granites—the "Laurentian granite"— as widely reported by Logan and coworkers and subsequently by Adams (1896, p. 42), Miller and Knight (1914, p. 11–12), Cushing *et al.* (1910), and many others.

[2] Widely distributed diabase dikes ("Keweenawan") and other scattered intrusives presumably of late Precambrian age are omitted from this discussion.

Divergence of opinion also exists concerning the interrelations, derivation, and sequence of emplacement of magma series in separated areas. In the northeastern part of the Grenville subprovince (northeast of the Saguenay River and Lake St. Jean), the abundant anorthosite and gabbro are intimately related and commonly interpreted as differentiates from a common magma type (Retty, 1944, p. 12–17; Faessler, 1942, p. 13–16; 1945, p. 10–11; 1948, p. 13–15; Claveau, 1949a, p. 40–41). At least locally, field evidence suggests that the gabbros evolved after the anorthosite (Claveau, 1949b, p. 21, 26). In most areas, however, this interrelation remains unknown. Commonly, younger granitic rocks (including syenitic types) and granitic pegmatites cut the anorthosite series and are clearly younger (Claveau, 1949a, p. 34–39; 1949b, p. 22–26; Greig, 1945, p. 24; Faessler, 1942, p. 11, 16–17; 1945, p. 11; Retty, 1944, p. 20). These granitic rocks appear to be emplaced largely during or at the culmination of deformation. An older pre-anorthosite "granite gneiss", "augen gneiss", or "gneissic granite" (Laurentian granite) is reported by Faessler (1942, p. 11, 12–13; 1945, p. 8) and Greig (1945, p. 8, 15–16, 24), but both Retty (1944, p. 10) and Waddington (1950, p. 6, 8–11) interpret similar banded gneisses and augen gneisses as migmatities formed by *lit-par-lit* injection and pervasive permeation of metasediments by younger (post-anorthosite and gabbro) granites and pegmatites.

The more recent discussions of igneous rock types in the region southwest of Lake St. Jean and the Saguenay River and into the valley of the Ottawa River (Fig. 1) (principally by Wilson and Osborne and reviewed by Dresser and Denis, 1944, p. 164–207) have employed the terms Buckingham series (Wilson, 1917, p. 19–21; 1919, p. 10–12; 1924, p. 28–32; 1925, p. 395–396), Lacoste series (Osborne, 1936c, p. 417–148), Morin series (Adams, 1896, p. 85J; Osborne, 1936c, p. 418–434) for what are inferred to be closely related igneous types ranging from anorthosite or gabbro through intermediate, syenitic, and granitic types. There is little agreement among these workers, however, regarding the interrelations of the various series. Here also the question of the existence of a "Laurentian" older granite is not settled. Wilson (1919, p. 10–12; 1924, p. 28–30; 1939, p. 266) has inferred that most or all of the rock types described as, or correlated by him with, the Buckingham series are closely related in origin and possibly are almost contemporaneous. A sequence of development is suggested, however, with the mafic types older than the granitic rocks, which seem to be represented as younger differentiates in a fractionated group. (*See, for example*, Wilson, 1925, p. 395, Table 1.)

Along the Ottawa River in the Quyon River-Rouge River area, the Buckingham series is believed by Wilson to be intruded by appreciably younger, post-metamorphic "batholiths" of syenite and granite (Wilson, 1924, p. 37–42; Dresser and Denis, 1944, p. 176–178).

The concept of a Laurentian granite—Trembling Mountain gneiss of Adams (1896, p. 42)—predating the anorthositic and gabbroic rocks of the Buckingham series has been reiterated especially by Osborne (1934; 1936c, p. 416–417) and Faessler (1948, p. 12–13). Osborne concludes (1936c) that another group of intrusives (Lacoste series) also predates the rock of the Buckingham series. The Lacoste series is described as consisting of igneous types "ranging in composition from gabbro to granite" (1936c, p. 417) and is described from several localities in the area northeast of the Ottawa River (1934, p. 15; 1935, p. 29; 1936c, p. 417–431). Osborne also has postulated that certain anorthosites, syenites, and granitic rocks (Morin series) postdate the regional folding of the Grenville series (1936c, p. 432).

With these diverse and conflicting interpretations in mind, it is of particular interest to note the interrelations of magma types to each other and to regional metamorphism in the Adirondacks, which lie less than 100 miles south of the lower Ottawa River valley.

The most thorough contemporary studies of the Adirondack igneous rocks are those of Buddington (1939; 1948; 1951) and Leonard (1951). Earlier investigators (Kemp and Alling, 1925, p. 31–35; Alling, 1932, p. 223–227; Cushing and Newland, 1925, p. 38–40; Balk, 1932, p. 9, 15) postulated an old Laurentian granite, but detailed reinvestigation indicates no data to support this hypothesis. Instead, anorthosites and gabbroic anorthosites appear to be the oldest rocks intrusive into the Gren-

ville series. They in turn are succeeded by gabbro, then syenites, and finally granites.

Buddington also demonstrated that, in the Adirondacks, all the major rock types except the granites (and subsequent undeformed diabase and syenite dikes) were emplaced prior to significant deformation of the Grenville series. This conclusion appears to rest on unequivocal data. The syenite bodies (Buddington, 1939, p. 73–134; 1948, p. 24–30) are in large part sheetlike to lenticular masses emplaced as sills along the bedding of the Grenville series. Their lithologic variations (ranging from shonkinitic syenite through pyroxene syenites and quartz syenites, to ferrohastingsite granite and alaskite) are the product of gravity differentiation. The earliest shonkinitic facies, with layers of feldspathic ultramafic rock, appear near the base of the sills, and successively more silicic fractions occur in order upward. These gravity-differentiated syenite bodies are now closely folded (Buddington, 1948, p. 25–27), but they must have solidified while the enclosing metasediments were essentially flat-lying or only gently dipping. Consequently, the only appreciable deformation which may be inferred before the solidification of the syenites is a very limited amount which may have developed along the margins of the anorthosite bodies as they were emplaced.

The granite complex of the Adirondacks clearly has evolved in part during or between stages of regional deformation (dynamothermal metamorphism) of the Grenville series and in part at the culmination of this deformation.

The evidence for a pre-orogenic environment into which the anorthosites, gabbros, and syenites were emplaced—presumably a "plateau type" environment—has been re-examined repeatedly by Buddington, by the writers, and others, and appears wholly conclusive. Whether a somewhat comparable physical history pertained in other parts of the Grenville subprovince in which similar igneous types appear remains a problem of major interest.

Data from the more recently investigated areas of southeastern Ontario seem to record a comparable history of intrusion. Harding (1946, p. 15, 20; 1951, p. 11, 21–28), Satterly (1942, p. 9, 17–19), Thomson (1943, p. 5, 8–14), and others regard the oldest post-Grenville intrusives as anorthosite and gabbro cut by syenite, granite, and alaskite. Throughout southeastern Ontario, granitic pegmatites cut all these rock types. The famous nepheline syenites of the Haliburton-Bancroft region, Ontario, are now interpreted as formed largely by replacement of paragneisses (Gummer and Burr, 1943, p. 286–287; Moyd, 1949; Thomson, 1943, p. 12–14). According to Satterly (1943, p. 17–19) and Thomson (1943, p. 5), the nephelinization was subsequent to the intrusion of basic rocks but succeeded by intrusions of alkali syenite, granite, and pegmatite.

Metasomatism

Metasomatic Changes Related to Anorthosite and Gabbro

Although anorthositic and gabbroic rocks are widespread and almost invariably inferred to represent solidified magma, few contact phenomena have been related to these rocks. This may be largely because most areas of anorthosite are mapped only in reconnaissance fashion, but it also reflects the attitude of some workers that anorthosites of the Grenville province represent but one differentiate of a parent magma from which rocks of gabbroic, syenitic, and granitic composition are derived, almost *in situ* (Wilson, 1919, p. 13; 1924, p. 28–32; Harding, 1951, p. 27; Balk, 1931, p. 390–413). As a consequence, several investigators regard distinctions of both age and exomorphic effects of specific igneous fractions as almost impossible (Wilson, 1924, p. 28–32).

Buddington (1939, p. 211–221) and others have concluded, however, that the Adirondack anorthosite was intruded well ahead of syenitic and granitic rocks. Seemingly well-documented examples of metasomatic effects induced by this anorthosite are discussed by Kemp (1921), Buddington (1939, p. 39–46), and others. These changes in wall rocks include garnet, pyroxene, wollastonite, feldspar skarns in the marble, and appreciable enrichment of the metasediments in sphene and apatite. In addition, Buddington (1939, p. 44–46) interprets many schliern, blocks, and lenses of mafic gneiss within the anorthosite as modified metasediments and skarn. Although the metasomatic effects are relatively much milder, Buddington (1939, p. 43) notes that "every type of phenomenon

found in the contact zones between limestone and granite is duplicated in the contact zones between anorthosite and limestone."

Elsewhere within the Grenville subprovince, the chemical changes thought to be induced in the Grenville type sediment by anorthosite or gabbro are at best hypothetical. Faessler, for example (1942, p. 13), has inferred that an appreciable body of augen gneiss northeast of Saguenay River has evolved as a product of contact metamorphism along the periphery of anorthosite.

Wilson (1917, p. 33–34) considers the magnesite deposits some 60 miles west of Montreal to have been formed in the marble by magnesia-bearing solutions derived from basic magma. Similarly, Adams and Barlow (1910, p. 23) speculated that some dolomitization of calcitic marble in the Haliburton-Bancroft area of Ontario was accomplished by magnesia-bearing fluids expelled from intrusions of basic pyroxenic rocks. Other noteworthy features reported as formed in conjunction with the emplacement of basic rocks include the *lit-par-lit* injection of quartzite by gabbro (Faessler, 1948, p. 27) and by diorite and gabbro (Wilson, 1917, p. 21, 33), and the injection of skarn by anorthosite (Buddington, 1939, p. 37).

Metasomatic Changes Related to Syenites

Metasomatic effects in the Grenville type sediment ascribed specifically to syenites are equally meager, although many reports make no attempt to distinguish effects of syenites from those due to granitic rocks.

In the Adirondacks however, Agar (1923, p. 148–156) has described in detail the occurrence of diopside, feldspar, wollastonite, and scapolite skarns with accessory sphene, quartz, and spinel. (*See also* Buddington, 1929, p. 87–88; Balk, 1932, p. 22–24.) These changes are confined largely to zones immediately adjacent to quartz syenite with infrequent and minor changes in the metasediments at points removed from the contacts. Agar (1923, p. 148–156) has attributed the metasomatism to the intrusion of a magma relatively poor in mineralizers but concluded that water, silica, chlorine, titanium, magnesia, and alkalis were introduced in the marble.

In Canada, along the lower Ottawa River, Wilson (1924, p. 63–95) observed quartz syenite containing fluorite. Locally he infers that a diopsidic skarn (1919, p. 32–34) as well as sulfide, pyroxene, and scapolite-bearing skarn (1924, p. 82–95) have formed in the marble through its interaction with volatiles expelled from the syenite. Syenites near Wakefield, Quebec, also are considered by Ambrose (1943, p. 22) to be the source of heat and water necessary to form brucite deposits in the marble. At other places near Amherst Township, Quebec, not far northwest of the type locality of the Grenville series, Wilson describes *lit-par-lit* injection of the metasediments by syenite (1917, p. 20–22, 33).

A somewhat reverse metasomatic effect is manifest in the conclusions recently arrived at by several workers, that the famous nepheline syenites of the Bancroft and near-by regions are formed in large part or wholly by syenitization of paragneiss. Thus Satterly (1945, p. 10–11), Moyd (1949, p. 736–751), Thomson (1943, p. 12–13), and Gummer and Burr (1943, p. 286–287) have concluded that these rocks are at least in large part of metasomatic origin formed by the replacement of paragneiss by fluids of necessarily complex composition and enigmatic origin.

Metasomatic Changes Related to Granites

In contrast to the few discussions of metasomatism induced by basic or intermediate igneous rocks, the effects of the alteration of Grenville type sediments by granitic fluids are noted in nearly every report. In many respects the changes induced in the metasediments show well-defined parallels throughout the subprovince, although the patterns of distribution of the altered rock are complex indeed. Distinct contact-metamorphic aureoles appear peripheral to the larger batholitic masses of granite and to some smaller more accordant intrusives. These aureoles include very large, irregular types, as well as small, sharply defined sheaths. (*See for example*, Adams and Barlow, 1910, p. 87–120, as compared with Buddington, 1929; 1939, p. 168–173; or Wilson, 1924, p. 82–95.) In many areas of granite, the igneous type is not clearly separable from granitized sediment and migmatite. Pegmatite dikes and veins ramify the wall rock or inject it *lit-par-lit*. In conjunction with some of the many granitic

intrusives, no well-defined contact aureoles appear. Nests and irregular masses of skarn and "contact" minerals are interspersed with relatively unaltered metasediment. Disseminations and well-defined lenses of metasomatic rock occur especially in the marbles without any visible connection to a well-defined granitic body.

Compositionally, however, the metasomatic changes attributable to granitic fluids are remarkably systematic, especially where changes within a given wall rock are considered.

Northeast of the Saguenay, where clastic sediments dominate the known Grenville type metasedimentary sequence, the most widespread metasomatic changes appear in the gneisses. *Lit-par-lit* injections of biotitic and hornblendic paragneisses are recorded in most reports. (*See for example*, Claveau, 1950, p. 9; Greig, 1945, p. 11–12; Faessler, 1945, p. 8, 9; Retty, 1944, p. 12; Ross, 1949, p. 10–14; Waddington, 1950, p. 8.) At many places, these paragneisses are known or readily inferred to be pervasively soaked and replaced by granitic fluids, with the formation of migmatites and metamorphic granite (Claveau, 1950, p. 13, 14–16; Retty, 1944, p. 12; Waddington, 1950, p. 8–11). Unfortunately, relicts of (chemically) little-altered metasediment are either uncommon, and difficult to identify, or simply unnoted. Consequently, the approximate composition of the parent sediment and the extent of the metasomatic changes remain unknown. Presumably the major components introduced are alkali silicates, especially potash feldspar and quartz.

A second major type of metasomatism which is related to granitic intrusives and may be important in this region is the replacement of marbles by amphibolites. Such pyrometasomatic amphibolites are inferred by Longley (1948, p. 11–13), Claveau (1949b, p. 12, 13), Faessler (1942, p. 12), and Greig (1945, p. 8–9, 13) in several widely separated areas. The absence of well-defined transitional rock types between marble and amphibolite and, in the more northeasterly areas, the scarcity of marble relicts contribute to make the hypothesis tentative at best. The hypothesis is offered in part because of analogies with areas in the western part of the subprovince (Adams and Barlow, 1910, p. 151–172; Buddington, 1934; 1939) and in part because of certain field relations, especially what is inferred to be relict bedding preserved in some amphibolites (Claveau, 1949, p. 13).

Wherever marble is found, silicated types also are recorded which contain substances readily inferred to be introduced from granitic magmas. The most obvious metasomatic effects appear in irregular masses or disseminated grains of scapolite, or scapolite and phlogopite (Claveau, 1950, p. 4), chondrodite (Ross, 1949, p. 11–12), pyrite (Greig, 1945, p. 27; 1950, p. 14), pyrrhotite (Greig, 1945, p. 27), molybdenite (Grieg, 1945, p. 27), and chalcopyrite (Longley, 1948, p. 11). Claveau reports a skarn of diopside, scapolite, sphene, phlogophite, pyrite, and graphite associated with a fluorite-bearing granite (1950, p. 14, 33). Some of the gneisses and schists also contain introduced sulfides, especially pyrite and pyrrhotite (Greig, 1945, p. 27), and chalcopyrite (Longley, 1948, p. 21; Retty, 1944, p. 27–28) which are inferred to be derived from granitic fluids.

In the subprovince southwest of the Saguenay, metasomatic changes in the Grenville series, readily attributable to granitic fluids, have been noted in almost every report. Clastic sediments almost surely derived from sandstones and from shales are widely injected and replaced by alkalis and silica. Many of the initially clean quartz sandstones have remained little altered (Osborne, 1934, p. 19–20; Miller, 1910, p. 10–12; Leonard, 1951, p. 25–26), whereas more complexly constituted clastic units, especially shales, are profoundly injected and granitized (Buddington, 1948, p. 36–43; Engel and Engel, Part II of this study; Harding, 1951, p. 11–16; Moorhouse, 1941, p. 606–607, 615–617; de La Rue, 1948, p. 13; Satterly, 1943, p. 10, 13; Wright, 1923, p. 15–17). In addition to metasomatic changes which produce rocks more nearly like granite, many of the paragneisses and schists contain sulfides and graphite which are inferred to be introduced by magmatic fluids. Pyritic, pyrrhotitic, and graphitic facies are especially widespread (Alling, 1918; Brown, 1936; Buddington, 1917; 1934, p. 209–214; Moorhouse, 1941; Osborne, 1939; de La Rue, 1948, p. 20; Smyth, 1912; Wilson, 1919, p. 38–41). A major problem throughout the province is whether most or all of the constituents for these minerals are of

sedimentary or metasomatic origin (Alling, 1918, p. 141–148; Buddington, 1934, p. 209–214; Wilson, 1919, p. 38–41).

Replacements of marble effected by fluids from granitic magmas are numerous and widespread. Well-defined contact aureoles around intrusives and pyrometasomatic deposits (at or near intrusive contacts) appear in association with many granitic bodies. More widespread, however, are the replacements of marble that vary greatly in size and form, and bear no well-defined spatial relation to obvious igneous contacts. These include uniform layers, irregular masses, nests, and disseminated grains of scapolite, phlogopite, apatite, quartz, diopside, tremolite, molybdenite, graphite, fluorite, chondrodite, tourmaline, beryl, serpentine, talc, iron sulfides, and many other minerals. The larger and more obvious masses of these minerals are commonly quite diopsidic and have been termed metamorphic pyroxenite by Wilson (1917, p. 25–33; 1919, p. 10–14; 1924, p. 32–35), Spence (1929), Wright (1923, p. 18–19), and others working in Canada.

These replacement bodies in marble of the Grenville type are discussed in the reports of almost every area of any size in southwestern Quebec, southeastern Ontario and the Adirondacks. (*See*, in Quebec, Claveau, 1950, p. 9; Faessler, 1948, p. 9; de La Rue, 1948, p. 19–20, 41–44; in Ontario, Adams and Barlow, 1910, p. 87–147; Baker, 1916, p. 15; Satterly, 1945, p. 9–10; in the Adirondacks, Brown, 1947; Buddington, 1934, p. 100–135; 1939, p. 166–181; Agar, 1923, p. 95–174.)

Most of these altered marbles have a very low iron content, but contain silica, magnesia, and alkalis well in excess of these components in less altered parts of the marble. Most or all of the alkalis and some of the silica have been introduced, as has chlorine (scapolite), fluorine (phlogopite, chondrodite, fluorite, tremolite), boron (tourmaline), water (talc, serpentine, brucite), and possibly appreciable magnesia.

The question invariably exists whether magnesia is largely introduced into the marble or redistributed and locally concentrated in deposits of talc (Wilson, 1926, p. 17–20, 24–28; Engel, 1949b), brucite (Ambrose, 1943; Harding, 1946, p. 26; Goudge, 1939), and magnesite (Bain, 1923; Osborne, 1936d; 1939; Wilson, 1917). Large-scale additions to the marble of magnesia derived from granitic magmas have been postulated by Adams and Barlow (1910, p. 192–226), Osborne (1936d, p. 63–91; 1939, p. 726), Wilson, (1917, p. 30–34), and others. Adams and Barlow (1910, p. 202) have concluded that many of the carbonate beds in the Grenville series of the Haliburton-Bancroft area were initially calcite, but have been dolomitized during emplacement of granitic batholiths, presumably by magnesia-bearing fluids derived from the granitic magmas. Much of the relatively pure dolomite is reported to be peripheral to the granitic batholith, whereas, outward from granite, and intermixed dolomite-calcite marble is described, in which dolomitic parts have formed at the expense of the limestone. Moreover, areas of marble farthest from the granitic batholiths include zones of pure calcite.

This interesting relationship is essentially the antithesis of that observed by the authors in the Balmat-Edwards district of New York. There the oldest stratigraphic relicts of marble are pure dolomite, whereas the highly injected and obviously silicified parts of the marble, and certain areas of it adjoining injection gneisses, are largely calcitic. Moreover, the paragenetic relations of calcite to dolomite indicate very clearly that magnesia has been removed from an earlier dolomitic rock. These relations do not preclude an earlier epoch of pervasive dolomitization, however, of which there are no obvious clues.

Wilson's and Osborne's conclusions that magnesia has been added to the rock from magmas seem based upon more tenuous data than those reported by Adams and Barlow. Osborne (1936d, p. 85) infers that the magnesite was derived from a fluid which "had the characteristics of a magma in the early stages [of introduction] but passed into a hydrothermal stage."

Little doubt seems to exist that much silica is introduced into the marble, especially in conjunction with many skarns. Some of this silica occurs as ramifying veins and irregular masses of quartz. As siliceous interbeds are widespread, however, and few precise stratigraphic studies have been made of large areas, very little is known about the proportion of quartz added compared with that merely redistributed. In the northwest Adirondacks, many of the areas

of siliceous marble regarded as probably sedimentary in origin by earlier workers actually consist almost wholly of silica introduced or concentrated during the injection and intrusion of pegmatites and granite.

The pyrometasomatic amphibolites and various occurrences of iron sulfides are examples of iron-rich replacements that appear in the marble with no well-defined spatial relationship to igneous bodies.

The most widely developed and clearly documented examples of metasomatic amphibolites are those discussed by Adams and Barlow (1910, p. 87–127, 157–172), and Adams (1909) in the Haliburton-Bancroft area of Ontario. Many of these amphibolites are dominated by hornblende and andesine, but some contain appreciable scapolite, sphene, biotite, chlorite, diopside, graphite, quartz, iron sulfides, and potash feldspar.

Similarly derived and constituted metasomatic amphibolites, with types transitional into marble, appear in the northwest Adirondacks. A comparable origin seems possible if not probable for amphibolites at many other places in the subprovince. Commonly the amphibolites derived by replacement of marbles include types nearly or quite indistinguishable from known ortho-amphibolites of the same region. Consequently, the origin of these rocks may be obscure, especially where metamorphism has blurred or obliterated obvious igneous or sedimentary features and where rock types transitional between amphibolite and parent types are lacking. One possible clue to the origin of some enigmatic amphibolites in the Grenville series is through studies of the amounts, the isotopic composition, and ratios of certain accessory elements in them. The ratios and amounts especially of Pb, Au, Sc, Cr, and Ni tend to be distinctive in some amphibolites of differing evolutionary development from a given environment and area (Engel and Engel, 1951). An even better genetic clue may lie in the isotopic composition of the lead in these rocks as contrasted with that in least-altered sediments and associated igneous rocks.

Iron and other base-metal rich replacements of marble include the veins, irregular masses, and disseminated grains of sulfides, especially pyrite, pyrrhotite, sphalerite, and gelena. Outstanding examples are the economically valuable zinc and lead deposits of the Montauban zone, Quebec (Osborne, 1939), Calumet Island (Osborne, 1944) near Quebec City, and in the Balmat-Edwards District, New York (Brown, 1936; 1947). The deposits at Calumet and Edwards appear to have many features in common as hypogene replacement veins. Those in the marble at Tetreault are closely associated with anthophyllite-cordierite skarns and, according to Moorhouse (1941), with pegmatitic fractions of granitic magmas.

True contact-metamorphic, or pyrometasomatic, deposits formed at or very near the contacts of granite and marble are known in detail from only a few regions. Some of the most striking contact aureoles are those as much as 200 feet wide surrounding phacolithic granites in the Northwest Adirondacks. These granites are alaskites which Buddington has concluded (1929; 1939, p. 152–175; 1948, p. 30–43) are satellitic to, and volatile-rich derivatives of, alaskitic granite more widely developed in the Adirondack core. The associated contact effects in the enclosing marbles are pyrometasomatic sheaths of amphibolite, oligoclase-quartz gneiss, and tourmaline pegmatite veins.

Other notable pyrometasomatic changes in the marble adjacent to and intimately associated with granites include the commercial magnetite-bearing skarns. Those which occur in peripheral parts of the Adirondack igneous massif (Buddington, 1951; Leonard, 1951; Newland, 1908) contain a complex assemblage of Ca-, Mg-, Fe-, and Mn-bearing silicates, together with iron oxides and sulfides. The skarn occurs as layers of masses in granite, commonly in association with calcitic marble relicts, and clearly has formed from the marble by progressive introduction of many substances, but especially silica and iron. Similar skarns occur in the Grenville-like marbles of northern New Jersey (Sims, 1953; Sims and Leonard, 1952).

Metamorphic Changes of Regional Scope

The emplacement of granitic rocks throughout the Grenville subprovince obviously is intimately associated with orogenic deformation. Consequently, most of the sediments referred to the Grenville series are thoroughly recrystallized and reconstituted as well as injected and

partially replaced. They are, moreover, profoundly deformed in most areas, although at least one intervening area of only slight to moderate deformation exists in Quebec west of the Saguenay River.

Marked variations in the patterns induced by regional, dynamothermal metamorphism, especially recrystallization, reconstitution, and deformation of the sediments, appear on both large and small scales. The best known of the large-scale variations are systematically related to large granitic massifs with a gross increase in degree and rank of metamorphism as the intrusives are approached. The more detailed variations in degree of dynamothermal metamorphism are referable to many causes but especially to differing degrees of permeation of the metasediments by fluids during metamorphism, and to anisotropies induced by changes in sedimentation, by small-scale intrusion, and by replacement.

Perhaps the best documented examples of regional variations in degree of dynamothermal metamorphism which can be related to large igneous massifs are those in the Haliburton-Bancroft area of Ontario (Adams and Barlow, 1910) and in the Adirondacks (Buddington, 1939; 1948; 1951; Leonard, 1951; Engel, 1949a). In both instances, a gross increase in degree of recrystallization and reconstitution of the Grenville series (as well as degree of metasomatism) is apparent in areas peripheral to the bulk of the igneous bodies. In the Adirondacks, there is also a general increase in the intensity of folding and shearing out of the Grenville series with an increase in proximity to the central igneous massif. In the northwest Adirondacks, for example, the zone of contact between the rocks largely metasedimentary in origin and those principally igneous is characterized by more nearly complete shearing out of the rocks, by greater distortion and obliteration of sedimentary features, and by more closely appressed and more steeply plunging folds (Buddington, 1939, p. 237–333, 1951, p. 223–246; Engel, 1949a).

A concomitant increase in metamorphic rank or grade accompanies these changes. In what are comparable argillaceous rocks discussed in Part II, the metamorphic facies change from the assemblage quartz-biotite-oligoclase to garnetiferous types and ultimately into sillimanitic facies which are closely associated with granitic rocks of the igneous massif.

Other large-scale variations in dynamothermal metamorphism of the Grenville series have been described by Wilson (1925, p. 392–395), Harding (1951, p. 11), and others in southeastern Ontario, and by Osborne (1936c, p. 408–415) in Quebec between the Ottawa and Saguenay rivers.

The examples in southeastern Ontario (Hastings County) are complicated by what Wilson (1939, p. 263–264) and others (for example, Miller and Knight, 1914, p. 3–13) believe are younger, less metamorphosed Precambrian sediments, which show many lithologic features in common with the associated Grenville series. These inferred younger sediments have been described as the Hastings series, for their known occurrences are confined to Hastings County, Quebec, although some investigators have concluded that they are merely less metamorphosed segments of the Grenville series (Harding, 1944, p. 55–56).

Most workers, however, in the region between the Ottawa River and the Madoc-Marmora areas of Ontario have recognized the progressive increase in metamorphism of Grenville series toward the east. Pelitic rocks are modified to greenschist types and quartz-biotite feldspar gneisses on the west but to garnetiferous and sillimanitic types to the east (Wilson, 1925, p. 392–395; Harding, 1947, p. 11). Accompanying these changes are more intense deformation and the appearance of more extensive bodies of igneous rocks, especially granites. (Compare Wilson's map of the Madoc area, Map 559A, 1940, with maps of the Olden-Bedford area some 50 miles to the east, Harding, 1951.)

A gross diminution in degree of deformation also is apparent between Hastings County in Ontario and areas to the northeast in Quebec (Osborne, 1936b, p. 202–203). Osborne also notes the divergences in orientation of major folds in these two areas. Belts of isoclinal folding west of the Ottawa River trend east, or northeast, whereas many folds east of the Ottawa River, in Quebec, are open types and trend northward. This region of open folds and moderate to gentle dips—"quasi-plateau structure" of Osborne (1936c, p. 413–414)—is bounded on the east by a second belt of close folding in the vicinity of the Saguenay River. The area of

least deformation appears to be that east of the large Morin anorthosite masses and is in general less invaded by granitic rocks than the more deformed areas. (*See* Adams, 1896, part J, the map and cross sections, and Osborne, 1936c, p. 413.)

Metamorphic Facies

The bulk of the metasedimentary rocks referred to the Grenville series throughout the subprovince exhibits mineral assemblages of the amphibolite facies or higher metamorphic ranks. In the clastic sediments for example which appear to be derived largely from argillaceous rocks, some garnet is present in most areas that have been mapped, and many gneissic segments are sillimanitic. North and east of the Saguenay, sillimanite appears to be present only locally (Greig, 1945, p. 8) although detailed petrographic work has not been done in most areas. Garnet is widespread, however, in quartz-biotitic and hornblendic paragneisses (Claveau, 1949b, p. 14; Faessler, 1945, p. 8, 9; Greig, 1945, p. 8; Longley, 1948, p. 11–13; Retty, 1944, p. 11; Ross, 1949, p. 12, 15).

Southwest of the Saguenay in Quebec, especially along and some 50 miles east of the Ottawa River, both garnet and sillimanite are recorded in most map areas. (*See, for example,* Faessler, 1948, p. 11; Moorhouse, 1941, p. 607; de La Rue, 1948, p. 16–17; Osborne, 1939, p. 714; Wilson, 1919, p. 7–8; 1924, p. 21.) Many of these rocks are reported to contain only small amounts of biotite and little or no hornblende. Almost all are quartzitic and feldspathic, but the composition of the feldspars varies widely. The least altered and injected types are inferred to represent reconstituted shales (Adams, 1896, p. 100J; Wilson, 1925, p. 392–394; Osborne, 1936b, p. 206).

Westward across the Ottawa River in Ontario, more biotitic types prevail in many areas. Most of these paragneisses are garnetiferous (Adams and Barlow, 1910; Harding, 1946, p. 18–19; 1951, p. 29; Meen, 1944, p. 13–14; Satterly, 1943, p. 10; 1945, p. 9; Wright, 1923, p. 15–18). Locally, however, sillimanitic facies of paragneisses are described (Thomson, 1943, p. 7). Meen (1944, p. 13–14) notes the occurrence of cordierite, staurolite, and andalusite with biotite and garnet in paragneisses, many of which are interlayered with marble.

The major paragneisses in the Adirondacks range from quartz-biotite-oligoclase types to garnetiferous (almanditic) and sillimanitic facies in close association with granitic rocks. Locally cordierite occurs with garnet, quartz, biotite, and sodic plagioclase. (*See* Part II.)

Almost all the mineral assemblages in the paragneisses throughout the Grenville subprovince have evolved in conjunction with extensive injection and soaking of the metasediment by magmatic fluids. In the Adirondacks and presumably in many other areas, much almandite and sillimanite in the paragneisses is related to zones of marked interaction of alkali-siliceous fluids and metasediment. These fluids, and the associated metamorphism, undoubtedly introduced local gradients of temperature, composition, and pressure and imparted greater mobility to many reactions. The fluids at least locally may have introduced alumina, now incorporated into sillimanite, and iron and magnesia into the garnet and biotite. They clearly resulted in modifications in the feldspars of many gneisses, especially with an increase of potash feldspar. Moreover the initial composition of the metasediments involved in these interactions undoubtedly varied appreciably at various parts of the sequence, and from place to place in the Grenville subprovince. Consequently, a comparable metamorphic facies at various localities cannot be interpreted as evolved either from similar parent rocks, or in an environment of similar temperature and pressure. Moreover, in most if not all areas, the system was not highly restricted, so that potash and other components were introduced, and iron, magnesia, and lime abstracted.

The least granitized amphibolites throughout the Grenville subprovince are dominantly hornblende-andesine rocks with either accessory clinopyroxene or biotite. This assemblage pertains whether the amphibolites are of igneous, sedimentary, or metasomatic derivation. Garnetiferous amphibolites are recorded at widely separated places in Canada and in the Adirondacks.

Most of the marbles throughout their area of occurrence in the subprovince contain both tremolite and diopside. Wollastonite occurs in

some pyrometasomatic deposits associated with one or more igneous rocks (Buddington, 1939, p. 41, 43; Claveau, 1949b, p. 12; 1950, p. 14; Wilson, 1919, p. 13–14) but is not widely developed in the marble away from these contacts.

In most areas of the Grenville type metasediments, retrograde metamorphic effects are noted. In the paragneisses, biotite is more or less altered to chlorite, sillimanite to sericite, and quartz and albite replaces the earlier-formed feldspars. The amphibolites are also chloritized and albitized at many places into greenschist facies, and much serpentine and talc are formed in the marble.

Deformation

Most of the Grenville type sediments have features clearly indicating profound deformation during metamorphism. In a majority of the mapped areas, the major fold axes and metasedimentary units trend northeast, although marked divergences appear, especially in the vicinity of large intrusive massifs (Fig. 1). The open forms and northward trends of folds in the areas east of Mont Laurier in Quebec (Osborne, 1936b, p. 202–203) have been noted. This region of open folds and moderate dips—"quasi plateau structure" of Osborne (1936c, p. 413–414)—is bounded on the east by a second belt of close folding in the vicinity of the Saguenay River.

The Grenville series in the Adirondacks (Buddington, 1939, p. 238, fig. 22; Engel, 1949a, Fig. 1) and the Grenville type metasediments in New Jersey (Spencer *et al.*, 1908; Bayley, 1941, p. 8–45), southern New York, and Pennsylvania (Frazer, 1939, p. 159–193) all are closely folded along northeast-trending lines.

Throughout the subprovince, many of the intimately associated igneous rocks, especially granites, syenites, and metagabbros, are elongate in accordance with the dominant lineaments in the metasediments. These igneous bodies are at least in large part grossly accordant and of sheet-like to lenticular form, although major transgressions of metasedimentary contacts are quite common.

The combination of elevated temperatures, volatile-rich granitic magmas and widely penetrative fluids from magmas, associated with regional dynamic metamorphism, imparted marked mobility to the rocks of the Grenville series (Satterly, 1942, p. 18; Buddington, 1929, p. 8).

The major rock types—marble, feldspathic gneiss, paragneiss, quartzites, and amphibolites—in many places show features indicative of solid rock flow on a large scale. (*See, for example*, in Quebec, de La Rue, 1948, p. 15, 39; Wilson, 1924, p. 20; 1919, p. 9; Moorhouse, 1941, p. 608; Ross, 1949, p. 17; in Ontario, Wilson, 1933; Satterly, 1945, p. 14; 1942, p. 18–19; Harding, 1951, p. 10–20; Meen, 1944, p. 24; Adams and Barlow, 1910; in the Adirondacks, Balk, 1932, p. 30–36; Buddington, 1936, p. 160–161; Brown, 1936, p. 240–244; Engel, 1949a.) The flowage phenomena are especially spectacular in the carbonate rocks. The more obvious features induced by flow are profound changes in form, especially thickness of the marble. Many of the thinned or disrupted segments coincide with flanks of folds, whereas the apical areas of these folds are enormously thickened and crenulated. Wilson (1933, p. 9) has inferred a thousandfold[3] increase of thickness in marble at the apex on the Claire River syncline, Madoc district, Ontario, and concludes that this thickening is induced by the transfer of material from the limbs of the syncline. In the Balmat-Edwards district, Brown (1936, p. 236, Fig. 1) has described the obliteration of marble members on the flanks of a major fold, accompanied by the accumulation of this carbonate in large masses at the apex of the structure. (*See also* Engel, 1949a, especially Fig. 9.) A somewhat comparable feature—clearly recognized at several places and to be inferred at many others—is the complete disruption of layers on one, usually the short, flank of asymmetric folds. Consequently hook-shaped forms appear in stratigraphic units (Brown, 1936, p. 245, Fig. 4; Martin, 1916, quadrangle map; Spencer *et al.*, 1908, Figs. 11, 12, 13, 14). In some areas of especially marked flowage the marble has "intruded" the associated more brittle gneisses and igneous rocks along fractures. In one of the more spectacular examples in the eastern Adirondacks (Balk,

[3] Either a misprint or miscalculation. Inspection of Wilson's map (1933, Fig. 1, and other data, 1933, p. 9) suggest the marble is about 10 times as thick at the apex of the fold as it is on the flanks.

1932) six large dikes of marble have been forced into fractures of the associated syenite. Balk notes that "like artificial columns, the marble dikes decorate this unusually interesting cliff and can be recognized from a great distance" (p. 30).

The differing degrees of mobility of marble and associated rocks are further manifest in the many tectonic breccias described, some of which are readily confused with true conglomerates. (*See, for example,* Adams and Barlow, 1910, p. 39–49.) Many beds of carbonate-rich marble have flowed like soft solids, whereas intercalated gneiss, quartzite, or amphibolite layers are shattered and dispersed. Numerous reports note these tectonic breccias, from most large areas where marble occurs (Baker, 1916, p. 8–9; de La Rue, 1948, p. 15, 39; Wilson, 1919, p. 9; Harding, 1951, p. 20; Engel, 1949a, p. 780–782).

Even the paragneisses, amphibolites, and quartzites show prominent flowage features, however, and, in some areas of appreciable granitic injection, no order of competence may be stated. Certain highly siliceous and silicated metasediments pervasively penetrated by magma or related fluids show some flowage features as pronounced as those in many parts of the marbles. The ptygmatic folds in the injection gneisses are examples of this type of flowage (Buddington, 1939, p. 163–166; *see also* Part II).

In spite of the tendency of many thin zones and some major units to flow or disperse, the bulk of the major rock motions and thus most dominant planes of secondary shear appear to have followed the sedimentary fabric. Large parts of the thicker, silicated paragneiss as well as thinner harder zones and beds have remained as semicontinuous sheets throughout the various stages of deformation. Prominent sills and lenses of syenite and older more mafic igneous rocks emplaced before or in the earlier stages of deformation served similarly as baffles which prevented the development of widespread prominent shears at large angles to the major lithologic units. Buddington (1951, p. 227–228) notes that in the Adirondacks the rudely accordant sheets and thick sills of quartz syenite have undergone less complex flowage and less small-scale distortion than the less competent metasedimentary host rocks. Accordingly, these syenites appear to afford the best means to work out some of the major structural features in that area. The enclosing metasedimentary rocks have been deformed into more numerous and complex folds. Consequently the preexisting semiconformable relations between syenite and Grenville series are blurred, and at least local "shearing off" of sedimentary rocks from syenite is apparent.

The shearing off (decolletment) of one metasedimentary unit from another, and the evolution of tectonic breccias have induced at least local, secondary unconformities in the rocks of the Grenville series. A remarkable example of the pseudo-unconformity of this type, between quartzites and marble of the Grenville series, appears in the Balmat-Edwards district, New York (Engel, 1949a, p. 779).

A corollary to these differing rates and degrees of movement between adjoining layers is the evolution of disharmonic folds (Balk, 1932, p. 34–36; Meen, 1944, p. 24, 26–27; Engel, 1949a, p. 779–782, Fig. 3; Osborne, 1936a, p. 15–16). An obvious question raised by these relations is whether large parts or all of the Grenville series have been sheared off a "floor" and moved laterally for appreciable distances. In conjunction with this question, it is noteworthy that no older floor to the Grenville series is apparent in most places, and there is abundant evidence that much subjacent rock has been remobilized to form components now intrusive into the Grenville series.

Because sedimentary bedding remained the dominant guide to the shearing and penetrative movements in the Grenville series, the most prominent foliation and lithologic layering induced by metamorphism is, in most areas, a quasi-bedding foliation. At least this appears to be true in the southwest area of the Grenville subprovince which has been studied in greatest detail. (*See, for example,* Osborne, 1936a, p. 12–13; 1939, p. 715; Moorhouse, 1941, p. 605–615; Buddington, 1929, p. 81–82; Engel, 1949a). In the Adirondacks and in most Canadian areas of the Grenville subprovince, maps are drawn with the strikes and dips of the diverse, major rock surfaces and layers plotted under a single strike and dip symbol. (*See* geologic maps as published by the Provinces of Ontario, Quebec, by the Dominion Government, and by the State of New York.) This practice

seems to do little practical violence either to gross stratigraphic or structural reconstructions. The thick units of gneiss and marble remain as distinctive masses which outline most major stratigraphic and structural elements.

This generalization is valid in spite of the fact that areas of intense deformation and alteration of the Grenville series exist in which bedding is obliterated by secondary surfaces, and some lithologic layers bear little or no relation to bedding. (*See, for example*, Engel, 1949a.) Many of these features are of very local extent and are commonly enveloped by larger areas in which at least gross stratigraphic synthesis is possible. A striking aspect of the resulting pattern is the abrupt transition frequently observed between the areas dominated by secondary features and those in which stratigraphic relicts are preserved. A most disturbing fact is, of course, that many variations in composition, texture, and form of units are not demonstrably primary or secondary in origin. Many of the variations in thickness of zones or beds are especially enigmatic and appear to bear no systematic or genetic relationship to other structural features. Some of these variations ascribed to metamorphism may have been induced by sedimentation, or possibly by a combination of erosion and sedimentation.

Metasedimentary Rock Types

Introduction

General discussion.—The distinctly layered form of the Grenville series and the famous marbles furnished the earliest clues to its metasedimentary origin. Emmons (1942, p. 38–59), working in the Adirondacks, and presumably some investigators in Canada (Adams and Barlow, 1910, p. 22) considered even the marbles to be igneous, largely because of spectacular flowage features.

The marbles are perhaps the most common and accepted means of establishing the identity of the Grenville series, or inferred equivalents in newly explored parts of the Grenville subprovince. (*See, for example*, Adams and Barlow, 1910, p. 35–39, and the publications of the Ontario and Quebec Departments of Mines, which discuss the Grenville series in various areas of southeastern Canada.) Many rocks passing under the name Grenville series, however, contain little or no marble, as Osborne (1936b, p. 202–204) and others have noted. This appears to be true of the possible lateral extensions of the Grenville series north of the Gulf of St. Lawrence in the northern and eastern part of the inferred Grenville subprovince (Fig. 1; Greig, 1945, p. 8; Waddington, 1950, p. 6–8) and elsewhere along its north-central boundary (Wahl and Osborne, 1950, p. 8–9, 25–26). Several other distinctive metasedimentary types constituting the typical Grenville series occur in these areas, however, as well as in close association with the marbles to the southwest (Fig. 1). These other types include quartzite, in part feldspathic and biotitic, hornblende-andesine amphibolites, more or less pyroxenic or biotitic, and quartz-biotite-feldspar gniesses, commonly garnetiferous and sillimanitic. The same rock types, with marble, also appear in the Precambrian outliers in the Green Mountains of Vermont, in southeastern Pennsylvania, New York, and in northwestern New Jersey (Sims, 1953; Sims and Leonard, 1952, p. 4–13).

Marble.—The major belts of marble, insofar as they are known in the Grenville series, occur in the southwest part of the subprovince (Fig. 1). They are especially prominent in the vicinity of the type locality (Logan, 1865; Osborne, 1936d), as well as westward into the Haliburton-Bancroft area (Adams and Barlow, 1910) and southward into the Adirondacks and Vermont (Whittle, 1894, p. 415). A very possible extension of the marble of the Grenville series appears in the Franklin limestone of New Jersey (Spencer *et al.*, 1908), New York, and southeastern Pennsylvania (Frazer, 1939; Bayley, 1941). North and east of Mont Laurier, Quebec, marble of the Grenville type appears to thin appreciably (Adams, 1986, p. 21J–28J; Ells, 1900, p. 22J–57J; Osborne, 1936b, p. 210), and northeast of the Saguenay River-Lake St. John area marble is known from only widely separated localities, where it forms layers commonly less than 50 feet thick (Ross, 1949, p. 11; Claveau, 1950, p. 9; Faessler, 1942, p. 12). In the rudely triangular region between the northwest Adirondacks, the Haliburton-Bancroft area, Ontario, and the type locality in Quebec, the marble constitutes from half to three-fifths or more of the Grenville series,

which probably ranges from about 8000 to 20,000 feet thick. In the northwest Adirondacks, for example, three major marble units and many thinner zones are exposed (Table1, Pt. II). The three thicker zones are, in aggregate, at least 8000 feet thick (excepting the siliceous and silicate interlayer). Prior to metamorphism these were at least 10,000 feet thick and possibly 12,000 feet thick. The associated clastic sediments in the Grenville series probably did not exceed 8000 feet in aggregate thickness.

Each marble belt can be traced along the strike for about 35 miles (Fig. 1, Pt. II). Probably the same thick marble belts show through the intrusive and metamorphic overprint in southern and central Hastings County, Ontario, south of Bancroft village, and may be traced almost continuously northeastward beyond the Ottawa River. This involves a distance along the lithologic trend of almost 100 miles. (*See* Ontario Dept. Mines Maps 52A, 53B, and Adams and Barlow, 1910, map.) The thick belts of marble in the vicinity of the type locality (Logan, 1865; Osborne, 1936a, map) likewise may be inferred to constitute lateral extensions of the marbles in the Bancroft and Adirondack regions. Osborne (1936a, p. 14) notes that at and near Grenville village these marbles are the most common members of the exposed Grenville series, which, as noted earlier, he estimates has a total thickness 5000 to 10,000 feet. Osborne, following Ells (1900, Pt. J), concludes that the marbles occur at and near the top of the exposed Grenville series in the region between the Ottawa and Saguenay rivers (1935, p. 60–61; 1939, p. 714). In the northwest Adirondacks, however, our reconstruction of the stratigraphic relations (Table 1 of Part II) results in a sequence the lower half of which is dominated by marble. Similarly the section as set up by Matt S. Walton (oral communication) in the eastern Adirondacks has the bulk of the marble near the base.

Very probably the marble in the Grenville series has an average aggregate thickness of several thousand feet or more throughout the region outlined by the LaChute area in Quebec, Bancroft, Ontario, and the Central Adirondacks. In this region of some 15,000 square miles, the marbles are involved in very large, closely appressed folds. Possibly some 20,000 cubic miles or more of carbonate rock were present before metamorphism.[4]

This region of thick marble belts may be as much as three or even five times larger, because its limits on the west, south, and southeast largely are unknown. In New York, however, there is some evidence that the marbles thin appreciably southeastward across the Adirondack area. Walton notes that in the southeastern Adironacks (Paradox Lake and Ticonderoga quadrangles) the exposed marbles of the Grenville series probably total less than 750 feet thick in a section possibly 4000 feet thick. At other localities in the eastern Adirondacks, Alling (1927, p. 799–800) describes a sequence some 1000 feet thick of which only about 10 per cent is marble. A roughly equivalent amount of marbles appears in the southern Adirondacks according to Ralph S. Cannon (oral communication), who estimates that in the Piseco Lake quadrangle marble constitutes no more than 10 per cent of the exposed Grenville series, there less than 5000 feet thick.

It is interesting to note, however, that in the Precambrian sequence of northwestern New Jersey and southeastern Pennsylvania, which is so strikingly like the Grenville series of the Adirondacks, several marble zones appear. The thickest zone (Franklin formation) has a steep dip and varies in width from half a mile to nearly 2 miles along the strike for about 20 miles from Ogdensburg, New Jersey, to Big Island, New York (Spencer *et al.*, 1908, p. 4; Pinger, 1950, p. 79). Although the thickness of the Franklin limestone is unknown, it doubtless approaches, and may exceed considerably, half a mile, for the least-deformed contacts of marble and associated gneiss are fairly straight, and the unit clearly is not repeated in a regional isoclinal fold. Folds with gentle to moderate plunges are abundant within the marble, but these cannot involve a systematic transport of material either in the direction of plunge, dip, or for more than the 20 miles of strike length exposed. Little is known regarding the thickness of the Grenville type marble in the Green

[4] In this figure, no compensation is made for the decrease in volume of the marble which has resulted from the interaction of primary dolomite and silica, and associated decarbonation during intrusion and metamorphism. Probably another increase in volume of 15–20 per cent is required to compensate for these losses.

Mountains, Vermont. (*See, for example*, Whittle, 1894, p. 414–417; Perry, 1928, p. 10–13.)

Although there is little doubt that the marbles of the Grenville type are much thinner in the northern part of the subprovince (northeast of Mont Laurier) than at the type locality, the inferred metasomatic origin of numerous amphibolites in areas northeast of the Saguenay River (Claveau, 1949a, p. 11–13; Faessler, 1942, p. 12) postulates beds of carbonate rock in the original sequence. As is discussed in the section on Amphibolites, however, many of these rocks may as well be interpreted as of igneous or tuffaceous origin, rather than as replacements of carbonate interbeds.

The marbles of the Grenville series show appreciable variation in texture, color, and in magnesia content. Coarsely crystalline types of marble are reported in many localities (Harding, 1944, p. 15; Satterly, 1942, p. 66; Baker, 1916, p. 5; Adams and Barlow, 1910, p. 194; Harding, 1951, p. 18). Harding notes component crystals of calcite 1 inch or more on a side in the Olden-Bedford area of Ontario, and Adams and Barlow (1910, p. 194) described areas of marble in the Haliburton-Bancroft area composed of calcite as much as 3 inches across. Balk (1932, p. 14) reports calcite crystals 3 feet in diameter from the eastern Adirondacks. In the Haliburton-Bancroft area and near the type locality (Osborne, 1936a, p. 16) the marble exhibits a marked increase in grain size near the large granitic masses. Away from these intrusives the marble changes from coarse dolomitic types to medium- or fine-grained calcitic rock and from white to blue.

Miller and Knight (1914, p. 43) and Meen (1944, p. 15–17) report that in some areas of southeastern Ontario marble which weathers brown is relatively dolomitic, whereas the blue-gray or white is low in magnesia. Pinger (1950, p. 79–81) notes that the Franklin marble is predominantly calcitic, white, and coarsely crystalline. Local areas of dolomite are gray to dark gray. Throughout much of the northwest Adirondacks the dolomitic areas of marble also weather gray, whereas the calcitic areas weather white. At other places in Ontario and Quebec, workers are unable to distinguish calcitic from dolomitic parts of the marble in the field (Thomson, 1943, p. 8; de La Rue, 1948, p. 21).

The proportions and interrelations of magnesian and calcitic marble in the Grenville series vary widely in most areas studied. (*See, for example*, in Ontario, Meen, 1944, p. 15–16; Harding, 1944, p. 63; 1946, p. 12–13; 1951, p. 20; Satterly, 1943, p. 52, 54; Goudge, 1935, p. 28–29; in Quebec, de La Rue, 1948, p. 17; Osborne, 1936d, p. 84–85; 1944, p. 27; Goudge, 1935, p. 3–4; in the Adirondacks, Buddington, 1934, the map of the Antwerp quadrangle; Smyth and Buddington, 1926, p. 13; in Pennsylvania and New Jersey, Miller, 1934, p. 294–296, 588–589, 600; Spencer *et al.*, 1908, p. 3.) Few detailed studies have been attempted to distinguish the origin and interrelations between relatively high and low magnesian types. Dedolomitization of the marble is a typical metamorphic process, and magnesian silicates of metamorphic origin are widespread. As noted in the section on Metamorphism, magnesite and brucite occur in many places as secondary minerals.

The origin of dolomitic parts of the marble is less clear; and different areas of dolomite are inferred to have different origins. In the northwest Adirondacks, many of the oldest carbonate zones are dolomite. These zones contain large areas of calcitic marble which is of metamorphic origin, formed as magnesia was selectively abstracted, moved appreciable distances, and refixed in masses of tremolite, anthophyllite, serpentine, and talc.[5] These relations prescribe only that much of the marble in the Grenville series of the northwest Adirondacks was dolomite in the early stages of metamorphism, or prior to the known metamorphism. Whether this dolomite was formed during diagenesis, or in subsequent processes whose more obvious effects are obliterated, remains purely speculative.

The relations are essentially the reverse of those noted in marbles in the Haliburton-Bancroft region (Adams and Barlow, 1910, p. 221–225); in the LaChute area, Quebec (Osborne, 1936a, p. 15–16; in the Franklin limestone in New Jersey (Pinger, 1950, p. 79–81); and elsewhere. In the Haliburton-Bancroft area, for example, Adams and Barlow (1910 p. 23, 35, 192–225) conclude that much of the dolomite is of metamorphic origin, formed as magnesia was introduced from both granitic

[5] These processes will be discussed in detail in Part III of these studies.

and basic intrusives. Osborne (1936a, p. 15–16) records very similar relations in the LaChute area of Quebec. Pinger (1950, p. 79–81) notes that in the predominantly calcitic Franklin limestone dolomitic areas are related to zones of shearing that are discordant to older banding (bedding) and probably secondary.

At the other widely separated areas, magnesia is inferred to have been introduced into a calcitic or only slightly magnesian marble, and in most instances a magmatic source is specified (Wilson, 1917, p. 33–34; Osborne, 1939, p. 717–718, 1944, p. 27). Most thick zones of marble are relatively siliceous, and a large part of his silica appears to occur as a sedimentary component. Some of the silica is in disseminated grains, but the bulk of it forms nodules, lenses, and quartzitic interlayers a fraction of an inch to as much as 100 feet thick (Harding, 1944, p. 65; 1947, p. 19; Baker, 1916, p. 6; Claveau, 1950, p. 14; Meen, 1944, p. 15; Adams and Barlow, 1910, p. 176–180–190–191).

In contrast to the siliceous nature of the marble, relatively few examples of primary aluminous types are known. Graphite is reported in the marble, however, in almost every area where the carbonate layers are studied in any detail. Its origin remains a major unsolved problem. Studies of the amounts and ratios of the isotopes C^{12}/C^{13} in this graphite recently have been undertaken, and these may serve as useful indicators. Nier and Gulbransen (1939, p. 697) and Rankama[6] (1948, p. 411, Table 3) record values of 87.9 and 89.3 respectively for the C^{12}/C^{13} ratio of carbon from calcite of the Grenville series.

Occurrences of bituminous carbonate layers and "stinkstones" or hydrogen sulfide-bearing marble are recorded by de La Rue (1948, p. 17, 21) from the Normingue and Sicotte map area, Quebec, and have been noted in Canada and in the northwest Adirondack Mountains by J. S. Brown (oral communication) and the authors. In addition pyritic marble is found almost everywhere that carbonate beds are explored. In the Adirondacks, the hydrogen sulfide-bearing layers are generally accordant with relict stratigraphic zones and closely associated with anhydrite, gypsum, natural gas, and traces of halite. J. S. Brown (1932; 1938) was the first to record these occurrences of calcium sulfates and natural gas in the marble of the Grenville series. The natural gas occurs in unfractured marble at depths of as much as 2000 feet below the surface (1300 feet below sea level) near Edwards and Balmat, New York, and includes methane, ethane, and nitrogen in appreciable amounts (Brown, 1932, p. 733). Brown recognized that the gypsum was of secondary origin but later (1936, p. 252–253) discovered that the gypsum was largely, if not wholly, an alteration product of anhydrite, which is "apparently interstratified in the Grenville limestone" (Brown, 1938, p. 1930). More recent detailed stratigraphic studies in the marble of the Sylvia Lake area, New York, by Brown and N. H. Donald, Jr. (oral communication) indicate almost unequivocally that the anhydrite forms sedimentary interbeds within the marble. Anhydrite and gypsum have been noted at other widely separated localities (Osborne, 1941; 1944, p. 17; Zimmer, 1947), invariably in association with sulfide-bearing ore deposits. This relationship together with some textural evidences that marble is replaced by sulfates led Osborne to conclude that the anhydrite and gypsum are of secondary origin formed during or after the emplacement of base-metal sulfides. The suggested relation of anhydrite to sulfide ores, however, is conceivably more apparent than real. Detailed studies in the Balmat-Edwards districts by Brown and Donald (oral communication) and the writers' field studies indicate that the anhydrite layers almost never form surface exposures. As a result the observations of anhydrite are confined to prospecting and mining areas where drill cores and underground exposures exist. Clear-cut examples of redistribution of sulfates are of course, to be expected in conjunction with metamorphism and ore deposition. The data suggest, however, that the anhydrite and gypsum evolved from sedimentary interbeds of gypsum. A second alternative is that both sedimentary and introduced anhydrite exist.

X-ray and petrographic studies of the anhydrite layers indicate that small amounts of halite are almost invariably associated with the calcium sulfates in the Balmat-Edwards district, New York. Accordingly, the halite also is inferred to be of sedimentary origin, although

[6] Citing data from the M.A. Thesis of B. F. Murphey, University of Minnesota.

some of it, too, was redistributed during metamorphism.

Paragneiss.—Quartz-feldspar paragneisses, either appreciably sillimanitic and garnetiferous or highly biotitic, appear almost everywhere that the Grenville-like rocks are found. Some paragneisses occur as thick, relatively monotonous zones with only minor interlayers of amphibolite, quartzite, and marble, whereas other gneissic layers are thin and intimately interlayered with associated metasediments. Paragneisses commonly rank second to the marbles in abundance in the areas of appreciable marble in the southwestern part of the subprovince. Eastward and northward, as the marbles thin or disappear, paragneisses tend to dominate the Grenville series. Nevertheless, the series is thought to thin in this direction (Osborne, 1936c, p. 410). Estimates of actual thickness of the gneisses are infrequent in published studies, and the lateral extent and interrelations of individual zones are little known.

In the northwest Adirondacks, the largest gneissic unit is about 3000 feet thick and constitutes one of the five major stratigraphic units within the exposed Grenville series. (*See* Part II.) What are probably lateral extensions of this same unit are exposed in the southern and eastern Adirondacks where Walton (oral communication) estimates that this or a very similar zone is roughly 1000 to possibly 2000 feet thick. The broad structural relations of the northwest Adirondack area suggest moreover that this is the rock unit described by Wright (1923, p. 15–18) in the Brockville-Mallorytown area, across the St. Lawrence River in southeastern Ontario. The available data hardly justify speculations regarding the extent of this gneissic unit beyond the above-noted areas. Longer-range correlations are most tempting, however, for very similar gneisses constitute major units in the Grenville series of the Haliburton-Bancroft area (Adam and Barlow, 1910, p. 181–188), in southern Vermont (Prindle and Knopf, 1932, p. 264–267), and in the highland area of northern New Jersey (Sims, 1953; Sims and Leonard, 1952, p. 10–11; A. F. Buddington, written communication).

Most of the thicker gneissic units within any area of the Grenville series are either quartz-sillimanite-feldspar or quartz-biotite-feldspar types in general much injected by granite. Both gneisses commonly contain garnet as well as accessory pyrite, sphene, apatite, and zircon. Graphitic segments also are common. Locally gneissic layers are gradational between the two major types. Other variants include highly quartzose, amphibolitic, and carbonate-bearing types, as well as types transitional into granitic gneisses.

The thick, relatively monotonous gneiss of the Adirondack region and southernmost Ontario as well as the thickest gneissic units in New Jersey and in the Haliburton-Bancroft area are of the quartz-biotite-feldspar type. In the Adirondacks, at least, the feldspar in the least-altered gneiss is oligoclase. With increasing degree of injection and granitization, potash feldspar forms at the expense of both plagioclase and biotite. Garnet and sillimanite are also formed in areas of appreciable interaction of gneiss and igneous granite. A feature of particular importance is that the chemical composition of the least-altered layers is approximately that of typical graywaches or certain tuffs. The interlayering of the gneiss with thick, widespread siliceous carbonate zones hardly suggests these rocks, however, as logical parent sediments. This problem is discussed again briefly and is dealt with at some length in Part II. Although available data are scanty, gneisses approaching the Adirondack type seem to be important units in parts of Ontario as well as in the region east of the Saguenay. In the major quartz-biotite gneisses of the Haliburton-Bancroft area, for example, Adams and Barlow (1910, p. 181–182, 184–185, 186, 188) observed appreciable plagioclase as well as potash feldspar. In view of the extensive injection of these gneisses by potash-rich fluids, some, if not most, of the potash feldspar probably is introduced. The original sediment appears to have approached the composition of the parent of the Adirondack gneiss. Similar sedimentary parents may be inferred for the gneiss in the Brockville-Mallorytown area from the data presented by Wright (1923, p. 15–18) and in other parts of southeastern Ontario from the analyses of gneiss published by Miller and Knight (1914, p. 26, 80).

Other approximate analogues of the Adirondack type gneiss may be inferred in the clastic metasediments reported to predominate in the

Grenville type sequence northeast of the Saguenay River. In numerous areas (Ross, 1949, p. 12; Claveau, 1950, p. 13; Greig, 1945, p. 11; Waddington, 1950, p. 9) quartz-biotite-oligoclase gneisses are described. Some of these gneisses and others approaching them in composition (Retty, 1944, p. 11; Claveau, 1949a, p. 12–15) also contain potash feldspar, but here, as in Ontario and New York, these rocks are injected and permeated by potash-rich fluids, and some of the potash feldspar must be assumed to be secondary. Unfortunately, no detailed modes, analyses, or other data are available.

Between the northeasterly areas of quartz-biotite-feldspar gneiss and those in the Adirondacks and Ontario, the sedimentary parents of major gneisses appear to have contained much less soda and a much lower ratio of soda to potash, and thus to have been more nearly equivalent to average shales in composition. The present gneiss is described as in large part a quartz-sillimanite-potash feldspar type (Adams, 1896, p. 49J–61J; Osborne, 1936b, p. 206; Wilson, 1924, p. 21; 1925, p. 393–394) with subordinate biotite and variable amounts of garnet. The bulk composition of these rocks (*see* Wilson, 1925, p. 393, Table II) approaches that of many shales although it is not clear whether all the analyzed material is regarded as essentially free from introduced material, especially potash. Assuming that potash-rich metasedimentary types are present, other rocks intermediate between these and the more sodic varieties also seem to exist (Osborne, 1944, p. 9, 19; Faessler, 1936, p. 29; Bain, 1923, p. 654–655). In addition the paragneisses described by Osborne (1939, p. 715, Table 1) from the Montauban area, Quebec, are essentially identical in composition to the Adirondack type. (*See* Part II for a further discussion of these problems.)

Quartzite.—Quartzites appear as narrow interlayers and zones throughout the known and inferred extent of the Grenville series. Northeast of the Saguenay River, the quartzites appear to be the dominant metasedimentary rock type (Claveau, 1950, p. 9; Longley, 1948, p. 11) in a few areas and common in most of those studied (Claveau, 1949a, p. 11; Longley, 1950, p. 7; Greig, 1945, p. 12; Ross, 1949, p. 12). In general the quartzites are intimately interlayered with amphibolites and paragneisses, in zones as much as 200 feet or more wide (Greig, 1945, p. 12; Longley, 1948, p. 11).

Southwest of the Saguenay, quartzite layers occur largely with gneisses and marble. Virtually every known belt of marble contains thin laminae and thicker beds of quartzite or quartzitic rock interlayered with carbonate. Although individual siliceous beds commonly are merely a few inches to several feet thick, the siliceous zone may be as much as several hundred feet thick. More massive quartzites, as much as 50 to 200 feet thick, are found on the northwest and southeast sides of the Grenville Lowlands of the Northwest Adirondacks. De La Rue (1948, p. 18) also notes a thick quartzite zone on Mount Sir, Wilfrid, Pope Township, Labelle County, Quebec, which is 1½ by 3 miles in extent with only minor intercalations of other rock types. Wilson (1919, p. 8) mentioned a zone of relatively massive quartzite half a mile wide in Amherst Township, Quebec.

The quartzose rocks in the Grenville series include relatively pure quartz types, as well as types intermediate between quartzites and gneiss, amphibolite or marble.

Northeast of the Saguenay, hornblendic, micaceous, and feldspathic quartzites appear to be more abundant than relatively pure silica layers. Many quartz-rich layers are closely associated with and transitional into amphibolites (Claveau, 1949a, p. 12; 1950, p. 9; Longley, 1948, p. 11; Faessler, 1945, p. 9). Micaceous quartzites also are reported from most localities studied. Grieg (1945, p. 12) mentions thick zones of biotitic and hornblendic quartzite which also are garnetiferous. Cross-bedding is described from quartzitic and conglomeratic rocks of doubtful affinities (Longley, 1950, p. 7). Within the more positively correlated parts of the Grenville series, cross-bedding is reported only very rarely although this feature may have existed at many places prior to metamorphism.

The quartz-rich beds and zones in the central and southwest parts of the subprovince are largely of two general types—those intimately associated with biotitic, garnetiferous, and sillimanitic paragneiss, and those within the marble. Some of those in the gneisses are garnetiferous (de La Rue, 1948, p. 17; Wilson, 1924, p. 122–123), and most are slightly or dis-

tinctly micaceous (Buddington, 1951, p. 74–78; Faessler, 1936, p. 30; 1948, p. 10; Wilson, 1919, p. 8; Cannon, 1937, p. 40–41).

Both pyritic (Faessler, 1948, p. 10; de La Rue, 1948, p. 17; Adams and Barlow, 1910, p. 173–191; Buddington, 1917, p. 4–6) and graphitic (Faessler, 1948, p. 10; Alling, 1918) types also appear. Feldspars, especially microcline and orthoclase, are common constituents of most quartzose layers in the gneiss. Inasmuch as most of these zones are injected and pervasively permeated by granite, much of this feldspar may be inferred to be secondary. Buddington (1951) believes the thick feldspathic quartzites along the northwest margin of the Adirondack igneous complex represent illitic sandstones. On the other hand, other workers postulate arkosic parent sediments for feldspathic quartzites in the Adirondacks and Canada. Interlayered quartzite and graywacke also are described by Harding (1944, p. 62–63; 1946, p. 14; 1951, p. 11–16).

The bulk of the siliceous laminae and beds interlayered with marble contain silicates, in large part formed by reaction of the pre-existing quartz and carbonates. Diopsidic, tremolitic, and phlogopitic quartzites are recorded from most marbles. The proportion of sedimentary to introduced silica in the Grenville series is a subject for speculation. The problem has been discussed at great length in conjunction with the so-called quartz mesh rock in the Adirondacks. This rock type consists of zones of siliceous marble in which much of the quartz occurs as a reticulating network with carbonate, diopside, and tremolite. Some relatively uniform layers of quartz also appear. Martin (1916, p. 22–23) and others assumed this siliceous marble to be sedimentary in origin, but as Buddington has noted (1934, p. 111) most of this "meshwork" silica is introduced into its present site in the marble. In the Adirondacks and elsewhere in the marbles of the Grenville series, however, as much as 15 per cent (by volume) of thick marble zones was quartz before metamorphism. Much of it is either pure quartz or silica plus secondary materials. In least-deformed areas, nodular as well as uniformly laminated types appear in relations essentially identical to those in younger cherty limestones and dolomites. Accordingly the question arises how much of the sedimentary silica is of clastic origin as contrasted with either organically secreted or chemically precipitated types.

Amphibolites.—Amphibolites appear everywhere that metasedimentary rocks of the Grenville type are recognized, and they constitute one of the major enigmas. Most of these rocks are largely hornblende and andesine. Other minerals may be present in excess of several per cent, however, especially augite, diopside, biotite, chlorite, scapolite, quartz, potash feldspar, and epidote. Accessory minerals commonly include calcite, apatite, magnetite, ilmenite, quartz, potash feldspar, and pyrite.

As early as 1910, Adams and Barlow argued convincingly (p. 62–128, 157–172) that large numbers of amphibolites in the region south of Bancroft, Ontario, have evolved as metasomatic replacements of marble, during granitic intrusion. Other investigators in many widely separated parts of the Grenville series have found abundant evidence of metasomatic amphibolites. In addition, many amphibolites are known to have evolved through dynamothermal metamorphism of gabbros intrusive into the Grenville series. Some are known or readily inferred to have formed by reconstitution of lava flows and tuffs, interlayered in, or closely associated with, the Grenville series. Also, numerous workers have suggested that some amphibolites represent reconstituted argillaceous dolomite layers, with little or no modification in composition. In many areas of the Grenville subprovince, neither the rock types transitional between the parent and the resulting amphibolite nor the parent rock are preserved, and the origin of the evolved amphibolite cannot be stated with any assurance. Ortho-amphibolites, metasomatic amphibolites, and presumably para-amphibolites have acquired nearly common chemical and mineralogical compositions and physical properties (Engel and Engel, 1951). The fact that most of these rocks, irrespective of origin, are appreciably modified by action of younger magmatic fluids greatly complicates any genetic studies.

Probably half the amphibolites associated with the Grenville series cannot be ascribed to a specific origin. This places an important condition upon studies of stratigraphic thickness

and associations of sedimentary rock types. In the area northeast of the Saguenay River, for example, amphibolites are widespread, but their parent rock types rarely are demonstrable. Faessler (1942, p. 12) describes hornblende-augite-plagioclase amphibolites closely associated with marbles and infers that most of these amphibolites represent reconstituted, impure limestone. Greig (1945, p. 9–10, 13) notes that about half the rocks described as Grenville series are hornblende-andesine amphibolites but is unable to find criteria establishing an igneous or metasedimentary origin. Retty (1944, p. 12) reports amphibolite bands up to 1000 feet wide. These bands are described as actinolite-plagioclase rocks, but their origin is unknown. Longley (1948, p. 12) notes that some hornblende-andesine amphibolites and hornblende schists show what appear to be bedding planes whereas other amphibolites are massive and look like intrusives.

In the central and western parts of the subprovince, where marbles are abundant and intimately related to amphibolites, the problems are much the same. Examples of well-established or highly probable metasomatic or paramphibolite are relatively few (Satterly, 1943, p. 11; Faessler, 1936, p. 29; Harding, 1944, p. 58–60; Adams and Barlow, 1910, p. 87–126, 157–172; Osborne, 1944, p. 9; Buddington, 1929, p. 167–168) compared to those amphibolites whose derivation from metasediments is merely inferred (de La Rue, 1948, p. 18–19; Faessler, 1948, p. 9; Scatterly, 1942, p. 7; Harding, 1944, p. 15–17; Meen, 1942, p. 13; Balk, 1932, p. 14–15; Cannon, 1937, p. 39–40; Cushing and Newland, 1925, p. 33–34; Buddington, 1934, p. 122; 1939, p. 11–12).

Origin of the Grenville Series

For almost a century, the above-stated rock types in the Grenville series, especially the gneiss and quartzite, with marbles, have been thought of as representing:

> "... a series of marine sediments originally laid down as alternating beds of shale, sandstone and limestone, and that as a consequence of the intense metamorphism to which the series has been subjected, the limestone has been transformed to crystalline limestone, the shale to sillimanite garnet gneiss and the sandstone to vitreous quartz. The reasons for this conclusion are (1) the association of the rocks of the series as interstratified beds similar to the manner in which marine sedimentary deposits occur; and (2) chemical analyses of the sillimanite-garnet gneiss show that this rock in every detail has the chemical composition of a shale; hence the three rock types, garnet gneiss, quartzite and limestone have respectively the chemical compositions of the three dominant members of the normal marine sedimentary series of the well sorted types." (Wilson, 1924, p. 23–23).

These ideas have been advanced for the Grenville series in the Adirondacks by numerous investigators (Cushing *et al.*, 1910, p. 26; Cannon, 1937, p. 9; Martin, 1916, p. 13) and for the Grenville series in Canada by Wilson, (1917, p. 20; 1919, p. 9–10; 1924, p. 22–23; 1925, p. 392–393; 1939, p. 262), Wright (1923, p. 20), and Dresser and Denis (1944, p. 164), in some instances for specific Canadian areas, but commonly as a generalization applicable to the Grenville series as a whole. Marked tectonism which would produce poorly sorted and incompletely weathered sediments rarely is specifically associated with Grenville sedimentation (Harding, 1944, p. 67; Meen, 1944, p. 13).

The concept of the Grenville series as a "normal marine sedimentary sequence of the well sorted types" actually seems, in many areas, a close approximation. At the type locality and for many miles west and south, the siliceous magnesian marbles are not only a dominating component of the total, known succession (Fig. 1), but the marbles also are either fairly pure or interlayered with micaceous schists and numerous essentially pure quartzose beds. In the northwest Adirondacks, a sequence of such quartzitic interlayers, each only a few feet thick, was traced for several miles along the strike. In the Balmat area, New York, some of these lithologic units clearly approach or satisfy the requirements of the blanket-type sedimentary unit (Krynine, 1948), with ratios of width to thickness greater than 1000 to 1. All the thicker units appear to have width to thickness ratios of 100 to 1 or more. Here are seemingly important qualifications of sedimentary sequences commonly formed in fairly stable shelf environments as opposed to types formed on crustal segments of marked instability and appreciable local relief (Krumbein and Sloss, 1951, p. 359–366).

Apparent anomalous association of sediments.—Many striking divergences from sedimentary

rocks commonly inferred to form in stable shelf environments are reported however from widely scattered parts of the Grenville series. The interested reader, persistent enough to explore the thousands of pages of description of these rocks, will encounter numerous references to conglomerates, volcanics, graywackes, arkose, and even iron formation. Moreover, the total thickness of the Grenville series throughout the southwest part of the subprovince (15,000–20,000 feet) is well in excess of most shelf deposits, at least on the stable part of the shelves.

Significant units of both conglomerates and volcanics are reported within the Grenville series in the very regions near and west of the type locality where clean quartzites are common and thick marble belts dominant (Fig. 1). The section is of comparable thickness and lithology southeast in the Adirondacks except for the volcanics and conglomerates. Most of the so-called "graywackes" in the literature on the Grenville series are reported from the same general areas in Ontario and southwestern Quebec in which volcanics and conglomerates occur with the Grenville series. The occurrence and distribution of these graywackes are not shown in Figure 1, however, because the rocks are evolved from a wide variety of sediments many of which clearly were not geosynclinal-type graywackes.

The assemblages described from the Grenville series are far too heterogeneous to be fitted neatly into any readily conceived sedimentary environment or into modern concepts of sedimentary tectonics. We may, of course, argue that the Grenville series is too complexly metamorphosed and too little studied to warrant attempts at correlation and sedimentary synthesis. An alternate, or dual philosophy is that the Grenville series comprises very ancient rocks, deposited at one of those early periods of the earth's history for which it is foolhardy to employ a too rigorous philosophy of uniformitarianism. Maybe, too, the recently proposed tectonic frameworks of sedimentation are so severely tailored that only a few sedimentary series can wear them well (Kay, 1947; Dapples *et al.*, 1948).

The picture of the Grenville series clears considerably, however, and many seeming contradictions disappear, if all citations of original sedimentary facies are excluded from discussions except those which are reasonably established in origin, and more clearly recognizable as parts of the Grenville series, though some enigmas persist and cannot be ascribed to inaccurate identifications or uncertain correlations.

IRON FORMATION: The two cited Canadian examples of "iron formation" are reported from the Cawatose map area, Quebec, near the northern margin of the subprovince (Wahl and Osborne, 1950, p. 26) and from the Actinolite-Cloyne area (east of Madoc) in southeastern Ontario (Miller and Knight, 1914, p. 3, 43–44). The "iron formation" in the Cawatose area was found in only one outcrop with 3 feet of marble and other rocks which *could* be Grenville. The rock in question "consists of alternating bands up to ½-inch thick, of clear, glassy quartz and fine-grained, red brown layers of magnetite and garnet" (Wahl and Osborne, 1950, p. 26). The total iron-bearing zone is 3 feet thick. The report notes that this may not be Grenville series, and the "iron formation" may be skarn. To at least the last possibility we subscribe enthusiastically.

The "iron formation" reported in the Grenville series near Madoc has been investigated recently by Meen (1944, p. 12–13) who notes that "in reality, this iron formation is a bedded quartzite . . ." which he concludes is not a part of the Grenville series.

The Adirondack examples of iron formation arise through the interpretation of the nontitaniferous magnetite deposits (Newland, 1908; Buddington and Leonard, 1944) as metamorphosed sedimentary iron ores in the Grenville series (Linney, 1943, p. 488; Walker, 1943, p. 520; Gillies, 1950, p. 85, 86). These deposits have been carefully restudied by Buddington (1951) and Leonard (1951). Their data demonstrate that the magnetite deposits are skarns and granite gneiss ores. This interpretation is far more consistent with the composition of the Grenville series in the northwest Adirondacks, where it is much less metamorphosed and modified. There, no vestige of a sedimentary iron formation can be found or readily inferred in any part of the Grenville series.

ARKOSE: The several occurrences of arkose

cited are from three places—the Piseco Lake quadrangle in the southern Adirondacks, areas along the Ottawa River, and the famous Haliburton-Bancroft area, Ontario. These examples are undoubtedly from the typical Grenville series, but whether they are initially arkosic sediments is highly conjectural. Two alternative hypotheses more consonant with the sedimentary facies association are that either these "arkosic" layers are secondarily feldspathized quartzites, or reconstituted argillaceous sandstones. Although many initially clear quartzite beds have escaped feldspathization, other readily inferred and proven examples of feldspathized quartzites are legion throughout the Grenville series. The other possibility has been advanced by Buddington (1951, p. 91–95) to explain one of the major feldspathic quartzites of the Adirondack region.

GRAYWACKE: The question of whether graywackes exist as interlayers and zones within the carbonate-rich segments of the Grenville series, as is implied in the literature, seems to be in large part a matter of definition. Pettijohn (1943, p. 941–943; 1949, p. 243–255) has pretty much determined the usage of the term "graywacke" adopted here. In general the composition of graywacke so defined "can be approximated by averaging about two parts of shale and one part of arkose . . . [except that] the result differs from normal graywacke in that potash is greater than soda instead of the reverse." As Pettijohn (1949, p. 251) has pointed out, this difference "means that graywacke not only is (1) the product of incomplete sorting, but also (2) the product of incomplete weathering."

Graywacke so defined is not merely a shaly sandstone. In Clarke's average shale (1924, p. 34) the Na_2O content (weight per cent) is 1.3, the K_2O content 3.24. Moreover in all specific examples of shales which comprise this average an excess of K_2O over Na_2O exists. In graywackes typical of the geosynclincal association of volcanics, pillow lavas, iron formations, and coarse clastics, the Na_2O content averages between 3.0 and 4.2 with K_2O at 1.75 to 2.75. (*See, for example,* Pettijohn, 1942, p. 250.) Such graywackes presumably are not formed under weathering conditions wherein the soda is liberated to go into solution. A relatively high soda content either must be retained by or added to the clastic particles deposited as sediment.

A rock of typical graywacke composition, if merely reconstituted into a metamorphic facies

TABLE 1.—CHEMICAL COMPOSITION OF GNEISS OF THE GRENVILLE SERIES, AVERAGES OF THE COMPOSITIONS OF THREE GRAYWACKES, AND THE COMPOSITION OF CLARKE'S AVERAGE SHALE

	Qb-A	G-1	S-1
SiO_2	70.90	69.69	58.10
Al_2O_3	12.17	13.53	15.40
Fe_2O_3	1.31	0.74	4.02
FeO	4.12	3.10	2.45
MgO	2.32	2.00	2.44
CaO	1.55	1.95	3.11
Na_2O	3.74	4.21	1.30
K_2O	2.87	1.71	3.24
H_2O^+	0.21	2.08	5.00
H_2O^-	0.05	0.26	
TiO_2	0.32	0.40	0.65
MnO	0.04	0.01	
P_2O_5	—	0.10	0.17
CO_2	—	0.23	2.63
SO_3	—	0	0.64
	99.60	100.01	

Qb-A Quartz-biotite gneiss from the Grenville series, northwest Adirondacks. Analyst Ledoux and Co.

G-1 Average of three graywackes (Taliaferro, 1943, p. 136)

S-1 Average shale (Clarke, 1924, p. 34)

of the rank characteristic of the Grenville series, would have the following very approximate composition: biotite 16–18 per cent, muscovite 2–4 per cent, oligoclase-andesine 38 per cent, quartz 40 per cent, iron oxides, apatite, and other accessories 2 per cent. Some chlorite, almandite garnet, and sillimanite might also be postulated in this facies. A critical fact is that the alkali and silica content especially of this rock (Qb-A) shows marked contrasts with either individual average shales found in "stable shelf" associations (table 1).

The printed discussions of graywacke reported in the Grenville series indicates that most of the writers did not have this type of rock specifically in mind. Harding (1946, p. 14), for example, who has used the term most

extensively, describes one "graywacke" from northeast of Lake Nipissing, Ontario, as composed "chiefly [of] quartz and microcline with small amounts of biotite." He states: "it appears . . . that the sediments that formerly existed in the area consisted in part at least of interbedded limestones, graywackes and quartzites." In another instance in central Frontenac County, Ontario, graywackes intimately interlayered with quartzites and limestones are described as "composed chiefly of hornblende, quartz, calcite, mica and feldspar" (Harding, 1951, p. 12), whereas others are stated to be "composed largely of hornblende" (p. 13), and still another important type includes "feldspar amphibolites" (p. 15).

Important aspects of the problem are that in most of the examples "the only sedimentary structure that has survived metamorphism is bedding" (Harding, 1951, p. 12), and the recrystallized and reconstituted rocks are interlayered with quartzites, paragneisses, and marbles. Hence the principal clues to the nature of the parent sediment would be the composition of least-metasomatized relicts and the rock associations. Both these features suggest that before metamorphism the rocks may have been anything ranging from impure shales and sandstones to calcareous interlayers. They certainly do not require or imply derivation from a typical graywacke.

The term graywacke also has been applied in the north Hastings area, Ontario (Thomson, 1943, p. 7), and in the area northeast of Madoc (Harding, 1944, p. 57; 61–62; Meen, 1944, p. 14) to interbeds in the Grenville series or to rocks thought to be the Grenville series. At these places, however, certain interlayered metasediments are described as slates (Meen, 1944, p. 14) and conglomerates (Harding, 1944, p. 61–62; Thomson, 1943, p. 5–8) in addition to marbles, quartzite, and paragneiss. Moreover, pillow lavas, volcanic agglomerates, and possibly tuffs appear to be closely associated with the Grenville series, if not actually interlayered with it (Meen, 1944, p. 8–18; Harding, 1944, p. 58–67; Thomson, 1943, p. 5–6). Accordingly, the inferred sedimentary sequence hardly suggests a single, obvious environment of deposition but possibly fluctuations or transitions between certain environments of shelf seas and those commonly envisaged in parts of geosynclines. On the other hand, no petrographic descriptions or analyses of the so-called graywackes are offered. Presumably graywacke is being used as a field term for almost any gray to dark gneissic and schistose rock inferred to have had a clastic origin.

VOLCANICS: Clearly identifiable volcanics in or closely associated with the Grenville series have been reported only in southeastern Ontario. Elsewhere in the subprovince, however, amphibolitic rocks of obscure origin may have evolved in part or *in toto* from igneous flows or tuffs or, of course, from marbles or younger intrusive rocks. In the localities in southeastern Ontario where indisputable volcanics appear, the interrelation of these rocks with the Grenville series is a matter of much conjecture. Miller and Knight (1914, p. 34, 39, 40, 41, 55), Harding (1944, p. 13; 1947, p. 9–11), Meen (1944, p. 19–23), and Satterly (1943, p. 8–9; 1945, p. 8–9) all infer that most of these volcanic rocks form either the base of the Grenville series or the "floor" upon which it was deposited. Thus, Meen (1944, p. 9–13) describes basic volcanics, agglomerate, and tuff at the base of the Grenville series in the Grimsthorpe-Barrie area and speculates that volcanics are interbedded with (1944, p. 13) the Grenville series. Satterly (1943, p. 8–9) reports volcanics northeast of Madoc and in parts of the Renfrew area northeast of Bancroft (1945, p. 8–9) and believed these underlie the typical metasediments of the Grenville series. Harding also describes lavas with minor sedimentary interbeds which are inferred to lie in large part below the Grenville series in the Kaladar and Kennebec townships of eastern Ontario (1944, p. 57, 60–62); he notes the possibility that some lavas may overlie the Grenville series (1944, p. 59). Thomson (1943, p. 5–6) considers these same alternatives for the volcanics of the North Hastings area. The volcanic rocks mapped by Harding in Kaladar and Kennebec townships appear to lense out eastward in central Fontenac County (Harding, 1951, p. 9–11) although the increasing degree of metamorphism in this direction obscures many of the geological relations.

The opinion that volcanics lie at or near the top of the Grenville series, in some of the same localities of southeastern Ontario noted above, has been reiterated by Wilson (1925, p. 394–

396; 1939, p. 264). However, Wilson (1933, Fig. 1 and p. 9) has noted pillow lavas[7] at the base of the exposed Grenville series in the Claire River syncline. If the major structure is as postulated, these volcanics must lie 800 to 1000 feet below the top of the Grenville series.

In Quebec, amphibolites inferred to be of volcanic origin are thought by Osborne to lie at the base of the Grenville series at numerous localities (Osborne, 1935, p. 61; 1936a, p. 15–16; 1936b, p. 203; 1936c, p. 409–410). The amphibolites are described as having "a composition intermediate between Daly's average basalt and andesite. This fact, taken in conjunction with other evidence suggests the amphibolites are metamorphosed tuffs or flows" (1936c, p. 409). Actually many amphibolites known to have formed by metasomatism of the marble in the Grenville series have compositions almost identical with those of typical ortho-amphibolites, and of mafic igneous rocks. Distinctions in origin of amphibolites in the Grenville series based principally upon conventional chemical analyses are open to serious question, no matter how closely these simulate an igneous average. Unless true relict pillow structures and ophitic or other unequivocal igneous textures and features are present they may well be of metasomatic origin—and much younger than the Grenville series.

There are also references to more acid volcanics. Dresser and Denis (1944, p. 172–173) state "rhyolite and andesite and hornblende schist that is almost certainly of volcanic origin" are associated with "Grenville series" in Bristol Township, Pontiac County, Quebec. This discussion is a review of the work of Wilson (1924) on his so-called "Bristol series," or Bristol phase of the Grenville series. Wilson himself was very cautious about identifications in his original paper, however, and noted (1924, p. 25):

"... considerable areas of fine grained, igneous rock are exposed that have the texture and mineralogical composition of either rhyolite, andesite, diorite or hornblende schist. With the exception of the rhyolite, these rocks have a mineralogical composition similar to some of the highly altered phases of the [younger intrusive] Buckingham series and it is possible that they are merely variations in these intrusives. They have been separately described, however, because their fine-grained texture and intimate association with the rocks of the Bristol series indicates that they may possibly be volcanic flows contemporaneous with the Bristol sediments."

Even assuming a volcanic origin for the rocks in question, they and the associated Bristol sediments may "... represent a younger series of rocks laid down unconformably on the Grenville series ..." (1924, p. 409). And so the record runs.

CONGLOMERATE: Unequivocal examples of conglomerate occur in close association with the Grenville series, but, as in the instance of volcanics, questions arise as to the exact interrelations. The bulk of these occurrences are in Hastings County and adjoining areas of southeastern Ontario, where volcanics also appear. In this region, Miller and Knight (1914, p. 9, 16, 26–31, 48, 74–75, 78–79, 87) concluded that essentially all the conglomerates were younger than the Grenville series and separated from it by a period of granitic intrusion as well as profound erosion. Wilson (1925, p. 392–395; 1933, p. 7–10; 1939, p. 263–264) also included the conglomerates of southeastern Ontario in an inferred younger sequence, the Hastings series, but concluded that no intrusive epoch separated the deposition of these two series, and that "there is little, if any, discordance in structure between them" (1939, p. 264). Meen (1944, p. 18–20) similarly interprets conglomerates of the Grimsthorpe-Barrie area, northeast of Madoc, Ontario, as appreciably younger than the Grenville series. He notes that in this area the two sequences readily are separable inasmuch as the conglomerates and associated metasediments referred to the Hastings series are more siliceous and less metamorphosed than the Grenville series.

In contrast, Harding (1944, p. 61–67) has described conglomerates intimately interlayered with marbles of the Grenville series, especially in Kalader and Kennebec townships which adjoin the Grimsthorpe-Barrie area mapped by Meen (1944). Harding states:

"The writer found it impossible to satisfactorily separate the Grenville series from the Hastings series either on lithological or stratigraphical evi-

[7] Wilson reports (1933, p. 9) that no pillow structures are found in these rocks in the area of the Claire River syncline. The writers observed well-defined pillows in the basic lavas at Sulfide (*see* Figure 1 of Wilson's paper) although at this point the pillow structure suggests at least a part of the section is in reverse order from that postulated by Wilson.

dence. Observations suggest that the Hastings-type conglomerates, containing boulders of limestone, might best be regarded as intraformational beds laid down within the Grenville series."

Conglomerates are unknown in other carbonate-rich segments of the Grenville series. East of the Saguenay, however, along the north shore of the Gulf of the St. Lawrence (Longley, 1950, p. 7–8) and inland north of Havre St. Pierre (Claveau, 1949a, p. 15–17) conglomerates occur as infrequent interbeds in metasediments dominated by quartz-mica schists and quartzites. Whether these rocks represent lateral extensions of the Grenville series is unknown. Claveau (1949a, p. 25–26) has suggested that the clastic-rich sequence north of Havre St. Pierre is post-Grenville and possibly pre-Huronian in age.

Inferred Environment of Deposition

A uniformitarianistic approach to the origin of the Grenville series seems consistent with most data, and, if this philosophy is followed, some interesting environments of origin are suggested. All these environments appear to have been marine, but with differences from place to place. The bulk of the carbonate-rich Grenville series, especially that from, say, the type locality southward into the Adirondacks and westward toward Bancroft, Ontario, seems to have been deposited in a large, persistently negative, although not highly unstable basin. The limits of this inferred basin, and many details of sedimentation within it, form an interesting subject of speculation. Periodically at least, waters in the basin appear to have been cut off from the open oceans and to have become abnormally saline. Perhaps the least equivocal features which suggest this assumption are the great thickness of the magnesian carbonate rocks and the interlayered anhydrite and halite. The carbonate zones (before metamorphism) must have averaged almost a mile in thickness throughout much of this region. In the northwest Adirondacks, carbonate zones totalled at least twice this thickness before metamorphism. Sediments of this type are highly consistent with the interpretation that the interlayered anhydrite is a primary sediment. It seems significant, moreover, that the anhydrite layers in the Adirondacks are closely associated with halite and "stinkstones" or bituminous and hydrogen sulfide-bearing dolomites, as well as with siliceous (cherty) dolomite and natural gas. The possibility has been pointed out that some of these substances, especially the hydrocarbons, halite, and anhydrite, were introduced during metamorphism. In the instance of the anhydrite, however, this alternative would require a highly precise stratigraphic control for the replacement process. The writers believe that the stratigraphic evidence, as well as the sedimentary associations, favors the tentative conclusion that the anhydrite and halite are integral parts of the sedimentary sequence.

If a large, at least intermittently restricted, basin of sedimentation did exist, its western margin may be inferred in the region northwest of Kingston, Ontario. There, volcanics, agglomerates, and conglomerates appear to be either interlensed or closely associated with typical marbles, quartzites, and paragneisses of the Grenville type. The obvious implication is that of transition westward into an environment of greater crustal instability in which positive as well as negative segments appeared from time to time. In contemporary terms, the relations could have been those of transition from a negative, possibly restricted basin into a miogeosynclinal environment. Thus Krumbein and Sloss (1951, p. 368–369) have remarked in connection with the miogeosynclinal associations that:

"Limestone may be abundant in some phases of miogeosynclinal sedimentation. Near the cratonic border, normal marine fossiliferous-fragmental and foraminiferal limestone may accumulate or be swept in from the shelf. Such limestones may aggregate several times the thickness of equivalent shelf deposits. The Mission Canyon and Rundle limestone (Mississippian) at the edge of the Cordilleran Geosyncline in Montana are of this type."

"Farther in the miogeosynclinal belt, the limestone is dominantly normal marine or other dense to finely crystalline types. The Knox dolomite (Cambro-Ordovician) of the Appalachian Geosyncline border is an example."

Very possibly some tuffs and graywackes occur in close association with the Grenville series in the areas of volcanics. These sediments must be inferred for, although relict features of conglomerates and pillow lavas are preserved, the primary textural and mineralogical

features of tuffs and graywackes are obliterated by metamorphism. Neither shard nor bogen structure remains in any of the possible tuffs, and most of the reported examples of graywacke, as noted earlier, may be evolved from very different sediments.

The striking similarity of many features of the metasedimentary sequence in northern New Jersey to the Grenville series in the Adirondacks and adjacent Canada suggests a possible southeastward extension of the inferred Grenville basin. To date, no anhydrite- or halite-bearing interlayers are known in the Franklin formation, nor has natural gas been detected. In most of its other features, however, the Franklin limestones and the associated gneisses derived from clastic sediments are the analogues of the Grenville units of the Adirondacks. One seeming complication is the fact that the marble layers exposed in the southern and eastern Adirondacks appear to total less than 750 feet thick, whereas the available data suggest that the Franklin limestone is at least 2000 to 3000 feet thick. Of course, much of the carbonate in the Grenville series in the southern and eastern Adirondacks may not be exposed. If most or all of it is represented in the exposures, a marked thinning of the carbonate units occurs across the Adirondacks from northwest to southeast. This might imply a shallow part of the basin in the southeast Adirondack area, but the same or a related basin could have had deeper segments extending into the eastern Pennsylvania, northwestern New Jersey area, or beyond.

Too little of the Grenville-type metasediments are exposed in Vermont to offer more than a suggestion of the volume or interrelations of these rocks. Marbles, quartzites, and paragneisses like those in the Adirondacks, and according to Bain (1938, p. 1823) like those near Shawinigan Falls, Quebec, are exposed.

The best region to study a marginal segment of the implied Grenville basin appears to be that northeast of the type locality, in Quebec. Data suggest that the carbonate units thin appreciably and exist either only locally or as very thin interbeds in the region north and northwest of the Gulf of St. Lawrence.

Conceivably a large part or most of the amphibolites which seem to form as much as a fourth to a half of the provisional Grenville series in this northeastern part of the subprovince represent completely metasomatized facies of the marbles to the southwest. For example, in the Metamec Lake map area, Saguenay County, Quebec (Greig, 1945), no marble is present in the sequence, but half the exposed rocks are amphibolite. Marble does occur 100 miles to the southwest, and Greig (1945, p. 13–15) speculated that much of the amphibolite could have been formed by complete replacement of carbonate beds. If part or all of this amphibolite is a replacement of marble, however, the disturbing question arises why there are not preserved some scattered rocks representative of intermediate stages in the metasomatic processes, and occasional remnants of the carbonate parent rock as well.

Far too little is known of the features of the paragneisses and schists associated with the amphibolites in the northeastern part of the subprovince to permit extensive speculations on their environment of sedimentation. They undoubtedly are derived from clastic rocks, especially sandstones and finer fractions. Relatively pure quartzites appear to be common at many places. The scattered arkoses described in this region are bound to be suspect unless there is little or no reconstitution or injection of the rocks. The associated quartz-biotite-feldspar paragneisses are little known but obviously could be the source of valuable data on the sedimentary associations and environments. Although no detailed field studies have been made of these gneisses and no modal or chemical analyses published, the fragmentary data on compositions of the minerals, especially of feldspar, suggest a rock type approaching the Adirondack paragneiss described in Part II.

If this is a correct interpretation, the parent sediment was much closer to a graywacke, tuff, or an aberrant sodic shale than to shales of more recent shelf seas, and a very different environment is implied from that suggested by an association of typical shales and quartz-rich sandstones. Far more work must be done, however, on these rocks and on their interrelations with the carbonate-rich Grenville series to the southwest before more extensive speculations are justified.

One extremely interesting relationship is

that of the orientation of major tectonic axes in the Grenville series to some of the known features of Grenville sedimentation. The basin in which carbonate-rich sediments were deposited in the southwest part of the subprovince appears to have extended from some point northwest of Bancroft, Ontario (Lake Nipissing?), southeastward as far as the Hudson-Champlain valley. This distance—roughly 450 miles—is a minimum value, for very possibly the Grenville type metasediments of New Jersey represent deposits in this same basin. If so, the extent of the basin in this direction was in excess of 600 miles as measured along the present surface of the earth.

Prior to deformation, a greater distance is implied, for this southeast direction is that of major foreshortening or constriction of the metasediments. Certainly there appears to be no evidence of dispersal of segments of the Grenville series along southeast lines. The suggestion is that of a basin of sedimentation subsequently deformed into folds whose axes lie at right angles to the greatest dimension (length) of its deeper parts. If this picture is correct, it hardly conforms to the deformational patterns in most younger geosynclines where folds evolve essentially parallel to the longest axes of the sedimentary basins.

Age

Throughout most of the Grenville subprovince, the Grenville series and its inferred equivalents are the oldest decipherable rocks. The age in years of the Grenville sedimentation is unknown, however, and for the present is subject to only the crudest speculation. What obviously are minimum values are obtained through analytical studies of minerals in pegmatites and granites intrusive into the Grenville series and of ores associated with granitic intrusions. Studies of this type undertaken to date include: analyses for lead and uranium in zircon, apatite, magnetite, and sphene in a granite from Essonville, in the Haliburton-Bancroft area, Ontario (Brown *et al.*, 1951), and in pegmatite minerals (Holmes, 1937, p. 204; Shaub, 1940; Marble, 1943; Ellsworth, 1932, p. 102–106; Ellsworth and Osborne, 1934; Nier, 1939, p. 159). In addition, determinations have been made on the helium content of pegmatite minerals and of magnetites associated with Adirondack granites (Hurley, 1951, Tables 2, 3). Values obtained range from about one billion years to a billion three hundred million years. The most precise measurements (Tilton, Patterson, Brown, *et al.*, 1952) on zircon and sphene from granite at Essonville, Ontario, indicate an age of 1050 ± 20 million years for the zircon and an age of about 1000 million years for the sphene. These ages appear to reflect about the age of the culmination of regional metamorphism and intrusion of the Grenville series—at the localities where samples were taken—because the analyzed minerals zircon and sphene, as well as other analyzed minerals, allanite, uraninite, and magnetite have formed at about this time. The length in time of the regional metamorphism, of the interlude between this metamorphism and the inception or cessation of sedimentation, remains unknown. The period between deposition of much or all of the Grenville series and its regional deformation and intrusion by granitic rocks in the Adirondacks, and possibly at other places, is of particular interest in that during this epoch the distinctive anorthosites, anorthositic gabbros, gabbros, and syenite complexes were emplaced. Although we may seek crude analogies from more recent earth history for data on the length of the regional metamorphism, and on the length of Grenville sedimentation, there exist no known younger intrusive epochs involving anorthosites. The data from the Adirondacks seem to require a plateau-type intrusion of anorthosites, gabbros, and syenites into the Grenville series. Consequently, undated Grenville events are respectively (1) deposition of 1 to as much as 4 miles of carbonate-rich sediments presumably in a basinlike area near the outer limits of, or adjacent to, an unstable crustal region (geosyncline?), (2) plateaulike intrusion of anorthosite, gabbro, and a syenite series, (3) regional granitic intrusion and severe deformation of the Grenville series. Accordingly, if we assume an average age of 1.10×10^9 years for the culmination of the Grenville orogeny, the inception of Grenville sedimentation may have been as early as 1.5×10^9 and probably exceeded 1.2×10^9.

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GRENVILLE SERIES IN THE NORTHWEST ADIRONDACK MOUNTAINS, NEW YORK

PART II: ORIGIN AND METAMORPHISM OF THE MAJOR PARAGNEISS

BY A. E. J. ENGEL AND CELESTE G. ENGEL

ABSTRACT

The major gneissic metasediment within the Grenville series of the northwest Adirondacks extends northeastward across the Grenville Lowlands for about 35 miles, though areas of different degrees of metamorphism and igneous intrusion. Within this region, the gneiss is interpreted to be grossly monoclinal, but overturned to form the southeast flank of a regional anticlinorium. The opposite flank of this structure probably lies just northwest of the St. Lawrence River in the Brockville-Mallorytown-Kingston areas, Ontario.

The gneiss is interstratified with thick zones of siliceous magnesian marble, thin quartzites, and schists. Two siliceous marble zones stratigraphically below the gneiss have a total thickness of about 8000 feet. A siliceous dolomite zone immediately above the gneiss (southeast of it) is at least 4000 feet thick and, with an overlying feldspathic quartzite, adjoins the central Adirondack igneous-rich massif. The gneiss itself is about 3000 feet thick and, except for thin interlayers of amphibolite and marble, the layers interpreted as relict beds are monotonous in texture and composition. These least-altered layers of gneiss are granoblastic, faintly foliated, quartz-greenish biotite-oligoclase gneiss in which the ratio of Na_2O/K_2O is approximately 1.3:1. Consequently the rock is far more sodic than typical shales. Layers of this composition are widely although sporadically distributed through the complex, and are injected *lit-par-lit*, replaced by and transitional into biotitic quartz-microcline-oligoclase granite, pegmatite, and alaskitic granite. Variants from these facies include garnetiferous and sillimanitic gneiss and migmatite, and tourmaline-bearing pegmatites.

The simple assemblage quartz-greenish biotite-oligoclase, found principally in those areas farthest from large bodies of igneous granite, undoubtedly represents not only the least-altered metasediment but moreover the lowest-rank metamorphic facies into which the parent sediment is reconstituted. This rock type is abundant northwest of Hyatt, New York, in that segment of the gneiss farthest from the central Adirondack igneous complex.

The alteration of the gneiss into various rock types reflecting increasing degree or rank of metamorphism as well as increasing interaction with magmatic fluids may be observed as the gneiss is traced northeastward toward Edwards, New York, which lies adjacent to the igneous massif. Alteration of the quartz-greenish biotite-oligoclase gneiss by granitic fluids commonly is accompanied by successive and marked decreases in biotite and in both the amount of plagioclase and in the per cent anorthite molecule of the plagioclase, as well as by a decrease in quartz content. Marked increases in potash feldspar content, particularly, serve as a useful index against which other mineralogical and textural changes may be plotted. As these changes appear in the gneiss, the greenish-brown biotite commonly gives way to a reddish-brown, probably more magnesian and titaniferous variety. A corollary to these successive mineralogical changes of gneiss toward granitic types are the chemical modifications involving, especially, a diminution in total iron, lime, and magnesia, and an increase in alkalis, particularly K_2O, which becomes dominant over Na_2O in many granitized facies. Intermediate types of this alkali-rich, potassic derivative of the gneiss most nearly approximate the composition of well-sorted shales and are possibly those considered by some earlier workers as representative of the sedimentary parent.

Textural changes include the development not only of migmatite, pegmatite, and equigranular granite, but also of widespread augen gneisses and "porphyritic" granite, both of which contain large porphyroblasts and possibly some phenocrysts, chiefly microcline.

The processes of injection and granitization seem to involve both magma and fluids from magma, which

permeated the gneiss, interacting with and replacing it. Where the interaction of granitic fluids and gneisses occurred near, along, and in the central igneous-rich complex of the Adirondacks, in an environment of higher temperatures, the reddish-brown biotite appears almost or quite to the exclusion of greenish varieties. In addition, almandite garnet and sillimanite are formed, in that order, as products of the interaction. Almandite and some orthoclase also have formed as new phases presumably reflecting increasing rank of regional metamorphism without significant chemical modification of the parent sediment. Some of the earliest magmatic fluids appear to have included iron-rich derivatives, which by metasomatism formed scattered ferriferous biotite and hornblendic layers in and along the gneiss. These are largely granitized by the subsequent and dominant incursions of potassic, low-iron magma and associated fluids. Considerations of volume relations, compositional features, and paragenesis in the gneiss complex indicate that the potash in the "injecting" fluids had its source outside the gneiss; that is, it could not have been derived from the gneiss itself by secondary leaching, differential anatexis, or related processes. Nor seemingly could the relatively high soda content of the least-altered gneiss represent an earlier, but secondary, inoculation of the gneiss or parent sediment after diagenesis. Accordingly, the soda to potash ratio which approaches 1.3:1 in the quartz-biotite-oligoclase layers is regarded as either inherent in the sedimentary particles, or added essentially at the interface of sedimentation.

If the composition of the quartz-biotite-oligoclase gneiss near Hyatt was inherent in the clastic particles deposited in Grenville seas, graywacke type sediments or tuffs are the most logical parent rocks. If soda was added to the clastic particles at the interface of deposition, or penecontemporaneously, the pre-existing sediment may have been one of the more common clay-weathering products. Unfortunately neither alternative is particularly compelling or more readily demonstrated than the others. The seemingly intimate and concordant intercalation of the gneiss with thick marbles and pure quartzites suggests that the gneiss was derived from shales or argillaceous sandstones which were products of marked residual weathering and good sorting. Graywackes, on the other hand, are presumed to imply a minimum of chemical weathering with rapid erosion, transportation, and deposition in an unstable crustal environment. Thick, monotonous tuffs are as anomalous within this Grenville association of sediments as are graywackes and hardly represent a logical parent to the gneiss.

To assume soda-rich clays as the parent sediment poses problems equally great. The uniform addition of soda to great volumes of the commoner clayey products of residual weathering is almost unknown as a normal marine process. Commonly potash, rather than soda, is added to the accumulating clays, forming illitic shales. In addition to potash, both calcium and magnesium have greater replacing power than sodium and thus would replace it in requisite marine environments. The principal justification for assuming that soda could have been added to Grenville clays lies in indications that parts of the Grenville seas were, periodically at least, abnormally saline and soda rich. The great thickness of the carbonate sequence, its content of magnesia, silica, anhydrite, and halite indicate this, although most or all of these substances except the silica could be of secondary origin.

If seas of abnormal salinity were involved, several possibilities suggest themselves. Some water-laid tuffs, altered tuffs, and clays are known to alter to zeolites and zeolitelike minerals. Thus, clinoptilolite, analcime, and apophyllite with more or less admixed clay are found as marine beds evolved through interaction of tuffaceous material and saline water. Some zeolites even form in open seas. The zeolitic rocks occur as both intermediate and end-stage products in the weathering of tuffs and probably of other rocks and form widespread uniform beds. As such they suggest a possible parent to the gneiss.

Another alternative is that during sedimentation sodic shales are formed, by base exchange, from clay products of marked residual weathering. Base exchange of this type is credible if the seas were abnormally warm, rich in soda, and depleted in other bases which have greater energies of exchange than soda. In this environment, common clay minerals such as montmorillonite are known to take up soda in exchange for a previously held base, especially calcium, magnesium, or hydrogen.

Lateral extensions of the Adirondack type gneiss should appear in the near-by parts of Canada where most gneisses in the Grenville series are described as "normal shales." It is hardly reasonable to infer that the lateral transition from a sodic to potassic sediment coincides with the international boundary. The data, though fragmentary, suggest that gneiss of the Adirondack type occurs in the Brockville-Mallorytown-Kingston areas and possibly for many miles beyond. Along and northeast of the Ottawa River, however, most gneisses described to date appear to represent derivatives of more normal shales or argillaceous sandstones. Accordingly the Adirondack gneiss may be inferred to pinch out to the northeast or grade laterally into metasediment probably derived from much less sodic parent clastics. In the northern and northeastern parts of the subprovince, however, paragneisses which seem to approach the Adirondack type are reported in numerous areas. The relations of these rocks to those in the southwest part of the subprovince are, unfortunately, a major enigma.

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Introduction

The oldest rocks found in the earth's crust almost invariably are of sedimentary and volcanic origin. The sediments commonly are graywackes, volcanic derivatives, lean siliceous iron formation, and related rock types which imply marked tectonism in both their source area and site of sedimentation. At least locally, however, the oldest decipherable metasediments in each major shield area are dominated by carbonate deposits and by associated beds which appear to represent fine-grained, well-sorted clastics. These sedimentary types suggest relatively old and widely distributed depositional areas marked by appreciable crustal stability, and comparably stable adjacent land masses upon which residual weathering predominated. The Grenville series is an outstanding example of a succession containing abundant well-sorted products of residual weathering. Moreover, the metasediments of the Grenville series may have been deposited synchronously with, or not long after, some of the "Archean geosynclinal deposits" to the north and west. The present paper is a discussion of the paragneiss, which forms the major clastic unit in the Grenville series of the northwest Adirondack Mountains.

Occurrence and Distribution of the Gneiss

The major gneiss unit in the Grenville series of the northwest Adirondacks, along with associated marble and other typical members, is well exposed in the area between Antwerp and Lewisburg, New York, on the southwest, and Russell and Hermon, New York, on the northeast (Fig. 1). This area lies within a broad, glaciated, and rolling lowland only 500 to 900 feet above sea level commonly referred to as the Grenville Lowlands of the Northwest Adirondack Mountains (Buddington, 1939, p. 5–7). The Lowland is bounded to the east and southeast by hills of granite and syenite which form the peripheral parts of the central Adirondack Mountains. The north and northwest boundary of the Grenville Lowland is defined by the St. Lawrence River and the associated broad belt of Paleozoic and glaciofluviatile sediments (Fig. 1).

Within the Grenville Lowland, the Precambrian metasediments of the Grenville series predominate by far over Precambrian igneous rocks. There the Grenville series is, in general, far less modified both physically and chemically than throughout most of the central, igneous-rich massif of the Adirondacks. Consequently, the combination of minimum metamorphism and intrusion, coupled with accessibility and good exposures over a large area, makes the Lowland area the best part of the Adirondack Mountains in which to study the origin and evolution of the Grenville series. Even in the Grenville Lowland, however, intimate mixtures of Precambrian metasediments and igneous and possibly more obscurely derived constituents occur. The prevailing and northeasterly lithologic trend (Fig. 1) is of course greatly complicated by S-shaped and other patterns of moderately to steeply plunging close folds (Martin, 1916, geologic map; Engel, 1949), by tectonic dispersal of the stratigraphic units and by the complex forms of intrusives and metamorphic hybrid rocks.

The gneiss is actually a complex of injected, replaced, and metamorphosed parts, most of which contain quartz, biotite, and feldspars as major constituents; segments of the gneiss have been referred to and mapped as quartz-biotite gneiss (Smyth and Buddington, 1926, p. 19–20). Other facies of the gneiss, especially those more intimately associated with large bodies of igneous granite, include garnet and sillimanite and large metacrysts of potash feldspar. These mineral names also have been employed in other designations of the rock as a garnet-biotite gneiss (Buddington, 1934, p. 116–117), garnet gneiss (Martin, 1916, p. 34–37; Cushing and Newland, 1925, p. 28–33;

Figure 1. Generalized Geologic Map of the Northwest Adirondacks

Showing the surficial distribution of major metasedimentary units (zones) in the Grenville series and their relations to both the Adirondack igneous massif and Paleozoic sediments. The metasedimentary zones are numbered in order of increasing age (Table 1). A grossly simplified interpretation of the structural features in the region is shown in Figure 2.

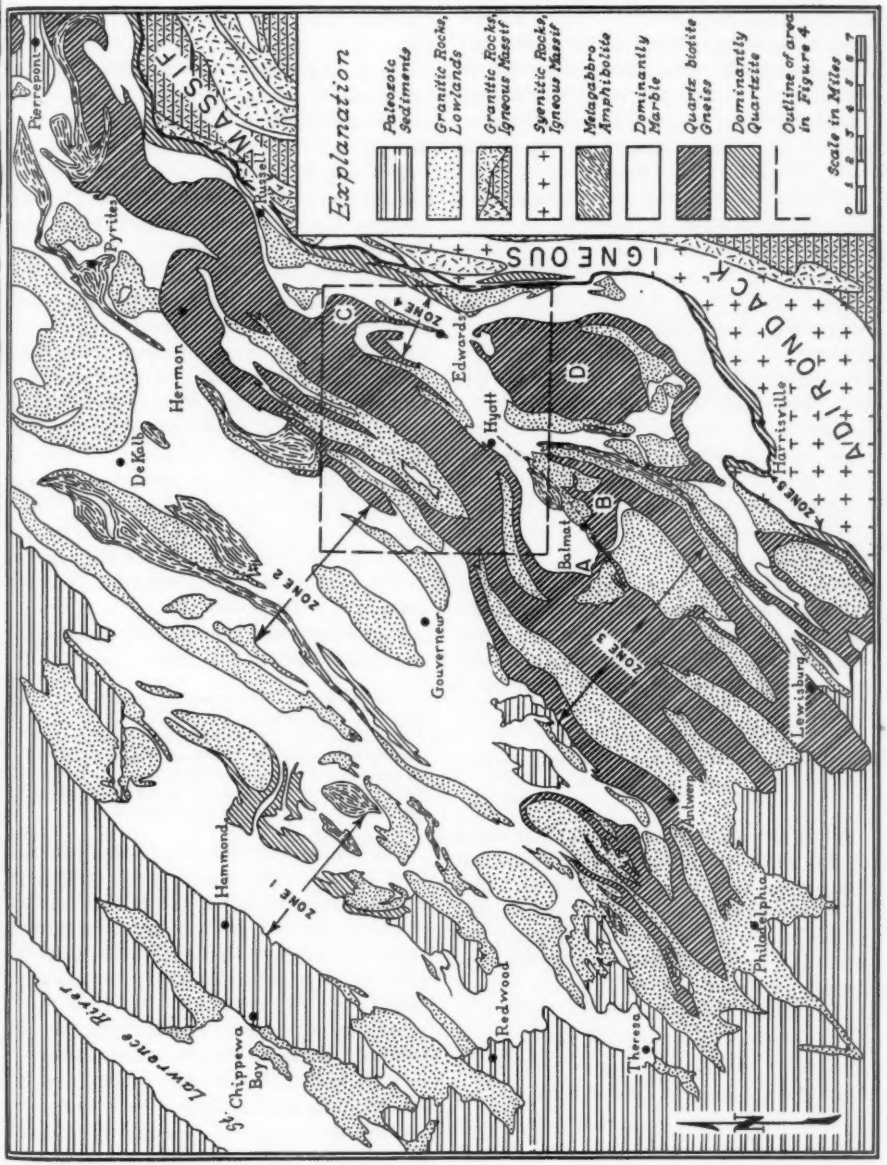
Explanation
Paleozoic Sediments
Granitic Rocks, Lowlands
Granitic Rocks, Igneous Massif
Syenitic Rocks, Igneous Massif
Metagabbro Amphibolite
Dominantly Marble
Quartz biotite Gneiss
Dominantly Quartzite
Outline of areas in Figure 4
Scale in Miles
0 1 2 3 4 5 6 7
ADIRONDACK IGNEOUS MASSIF
Perrepont
Pyrites
Hermon
DeKalb
Edwards
Hyatt
Balmat
Harrisville
Gouverneur
Hammond
Redwood
Chippewa Bay
St. Lawrence River
Theresa
Antwerp
Philadelphia
Lewisburg
ZONE 1
ZONE 2
ZONE 3
ZONE 4
ZONE 5
A
B
C
D
N

FIGURE 1

Brown, 1936, p. 236–238), and sillimanite schist and augen gneiss. Such names indicate various mineralogic facies of the gneiss, but they also have introduced ambiguity and confusion, for the stratigraphic relations and structural features of gneisses having all these minerals at one place or another are interpreted very differently by different workers.

Northeast of Edwards and Hermon, New York, the segments of the gneiss that are clearly derived from a common, genetically associated metasediment are especially difficult to establish. Highly deformed and chemically modified parts of the Grenville series are complexly interspersed with marbles and with amphibolitic and granitic rocks. (*See especially* Martin, 1916, quadrangle map, and Dale, 1934, preliminary quadrangle map.) Relicts of the gneiss with its characteristic northeast lithologic trend (Fig. 1) do appear, however, and north of Colton they pass under the overlap of Paleozoic and Cenozoic sediments. (*See also* Reed, 1934, quadrangle map.)

West and southwest of Antwerp, the gneiss and adjoining metasediments of the Grenville series are also obscured by the overlap of Paleozoic sediments (Fig. 1; Buddington, 1934, maps of the Hammond and Antwerp quadrangles).

Stratigraphic Relations and Structural Features

When the form and stratigraphic relations of this gneiss are known, the structure and stratigraphy of much of the Grenville series in the Northwest Adirondacks will likewise be understood. The writers now interpret the gneiss as a single major zone forming the overturned, southeast flank of a regional anticlinorium whose opposite northwest flank—if it exists—should lie northwest of the St. Lawrence valley, possibly as the gneiss belt in the Brockville-Mallorytown and Kingston areas of Ontario, Canada. (*See* references to the "garnet and biotite gneiss" Wright, 1923, p. 15–18; and Baker, 1916, p. 4–5.) Evidence for the Adirondack segment of the anticlinorium seems good but not unequivocal. Other workers of equal or greater experience in the region have suggested quite different interpretations at various times. (*See, for example,* Cushing and Newland, 1916, p. 16–17; Brown, 1936, p. 236–244.)

The stratigraphic sequence implied by the interpretation of the structure as an overturned anticlinorium is as shown in Table 1. The gneiss is believed to be interstratified between zones of siliceous marble each of which has a minimum thickness of 4000 feet. The two marbles stratigraphically below the gneiss lie northwest of it and appear to form the core of the anticlinorium. The marble belt above the gneiss (southeast of it) is overturned to the southeast and is separated from the Adirondack igneous massif by a zone of feldspathic gneiss which Buddington (1951) believes is a reconstituted illitic and calcareous shale. These structural and stratigraphic relations are shown in generalized form in the plan and vertical section (Fig. 2). This interpretation is very different from those advanced earlier by Cushing and Newland (1925, p. 17) and Brown (1936, p. 240–244), but the rock sequence is almost identical with that suggested by Buddington in 1934 (p. 135–138).

In a more recent publication, Buddington speculated (1939, p. 243) that:

> "In the light of the present available data, one possible interpretation of this Grenville belt is that it represents a part of the northwest limb of a major synclinorial structure, complexly folded and strongly overthrust as a wedge toward the southeast along a zone of pronounced flowage and mylonite within the belt of syenite and Grenville."

The writers' interpretation is essentially the same as or complementary to and confirming Buddington's suggestion, except that he appears to place the anticlinorial core farther northwest, possibly in Canada (Buddington, 1939, p. 237); the writers show it in zone 1 (Fig. 2).

Seemingly, the only tenable alternative to this interpretation is that the metasedimentary rocks in belts 2 to 4 (Fig. 2) compose a tight synclinorium mashed against and around a dome of gneiss south of Edwards. This interpretation, advocated by Brown (1936), assumes two major gneiss formations in this area, rather than the one indicated in Table 1. Neither the details nor the validity of this interpretation will be discussed here but are treated in detail in Part IV of these studies. Irrespec-

tive of which interpretation is correct, however, there persists a most critical relationship, pertinent to the present discussion. All the gneiss, with the possible exception of the large elliptical mass south of Edwards (at D, Fig.1) forms a stratigraphic unit intercalated between the two large and distinct zones of marble in the Grenville series. That is, the original sediments now metamorphosed to gneiss must have been laid down in an episode sandwiched between two major periods of carbonate deposition. Moreover, studies of the interrelations of relict beds in the gneiss and in the adjoining marbles and of the stratigraphic contacts of these units reveal no marked unconformities between the gneiss and either marble.

The possibility cannot be excluded that slight unconformities or marked disconformities existed but now are masked by metamorphism. Many field data suggest, however, that these major units are all components of a fairly continuous and closely related stratigraphic sequence. In Figure 3, for example, are shown what appear to be conformable stratigraphic relations between the southeast margin of the gneiss complex northwest of Balmat and the adjoining part of the overlying marble zone.

Both the marble and gneiss contain very definite layers which appear from place to place through the metamorphic overprint in unique, mappable sequences. These sequences clearly predate the detectable metamorphic phenomena and are interpreted with assurance as relict beds and stratigraphic zones. The relict beds and stratigraphic zones in the marble where it is least deformed lie essentially parallel to the marble-gneiss contact and to the oldest major foliation in the gneiss for many miles. Furthermore, the beds of marble are relatively pure dolomite with fine-grained, clean quartz

TABLE 1.—GENERALIZED STRATIGRAPHIC SEQUENCE IN THE GRENVILLE SERIES, NORTHWEST ADIRONDACKS, NEW YORK

Major rock unit		General lithology	Approximate thickness (Feet) AM = after metamorphism BM = before metamorphism
Geographic designation	Common designation		
Inferred Top of Exposed Sequence			
Harrisville-Russell feldspathic gneiss, Zone 5 (Pl. 1 and Fig. 1)	Upper feldspathic gneiss or feldspathic granulite	Quartz-microcline gneiss, in part pyroxenic, biotitic and locally hornblendic	AM = 500–1000 BM = 800–1200
Natural Bridge-Balmat-Edwards-West Pierrepont marble complex Zone 4 (Pl. 1 and Fig. 1)	Upper marble belt.	Dominantly dolomitic marble with interlayers of pyritic graphitic schist, feldspathic, biotitic and pyroxenic gneiss.	AM = 4000 BM = 6000
Lewisburg-Antwerp-Hermon gneiss complex, Zone 3 (Pl. 1 and Fig. 1)	Quartz-biotite gneiss or major gneiss complex	Quartz-biotite-feldspar migmatite, in part garnetiferous and sillimanitic. Includes several marble zones and numerous thin interlayers of amphibolite	AM = 2800 (exclusive of most granite) BM = 3200
Gouverneur-Pyrites marble complex, Zone 2 (Pl. 1 and Fig. 1)	Gouverneur (central) marble belt	Dominantly marble with scattered interlayers of quartzite and feldspathic and pyroxenic gneisses	AM = 4000 BM = 5500
Rossie-Black Lake metasedimentary belt, Zone 1 (Pl. 1 and Fig. 1)	Black Lake metasedimentary belt	Complexly interlayered marble, quartzite and biotitic, feldspathic and pyroxenic gneisses	AM = 4000 BM = 6000
Inferred Base of Exposed Sequence			

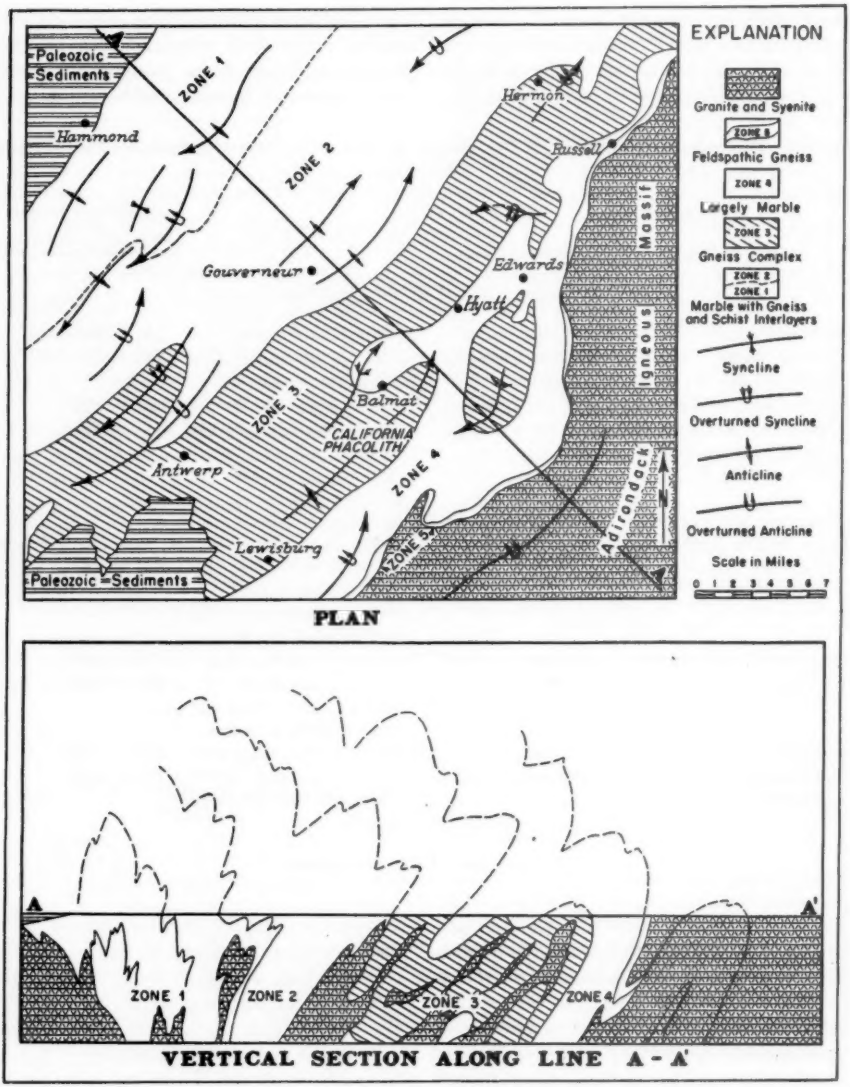

FIGURE 2. HIGHLY GENERALIZED PLAN AND VERTICAL SECTION OF THE MAJOR STRUCTURAL FEATURES IN THE GRENVILLE SERIES OF THE NORTHWEST ADIRONDACKS, NEW YORK

The gross structure is interpreted to be that of the center and overturned, southeast flank of a somewhat bulbous anticlinorium. Major segments of the axes of many of the second- and third-order folds are oriented athwart this gross structure although they have clearly formed in conjunction with it. This axial inversion—that is, cross folding—is necessarily minimized in the map plan to permit the reconstruction of fold segments.

laminae and some quartz lenses possibly formed from chert nodules. The pyritic, graphitic schist (Fig. 3) undoubtedly has evolved from an argillaceous and somewhat calcareous sandstone, which may have contained much of the iron and sulfur combined in the pyrite as sedi-

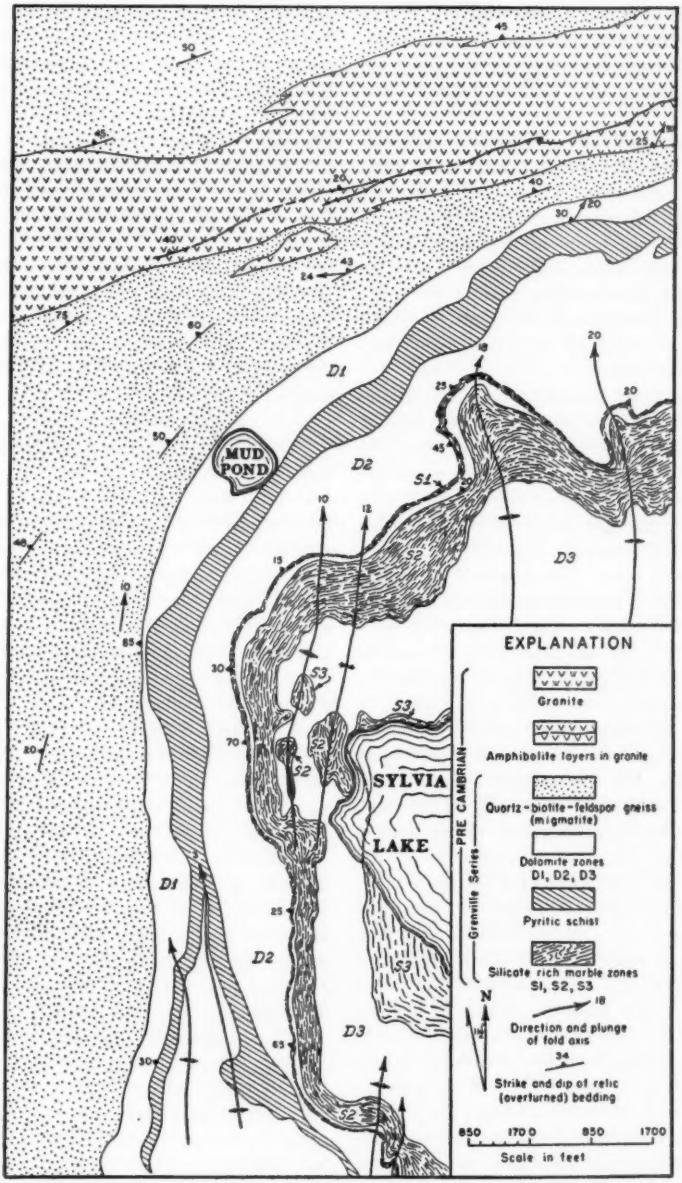

FIGURE 3. MAP OF A SMALL AREA WEST AND NORTH OF BALMAT AND SYLVIA LAKE, NEW YORK

Showing the essentially accordant relations between the stratigraphic units in the marble, the contact of marble and gneiss, and the relict bedding in the gneiss. The major variations in widths of outcrop and thickness of individual zones are demonstrably secondary, and along with the folded features have been induced by dynamic metamorphism. The area is at the southwestern apex of the Balmat-Edwards syncline (Fig. 2).

mentary or diagenetic constituents. Neither gneiss nor marble contains any clastic facies which before metamorphism could have exceeded in grain size a medium-grained sandstone.

Other features in the gneiss and marble suggest that they are integral parts of a fairly continuous sequence. Within the gneiss are several relatively thick and thin intercalations of siliceous magnesian marble lithologically similar to that in the major marble belts. In addition the northwestern contact of gneiss and marble—the base of the gneiss?—exhibit what appears to be some small-scale interlayering of the two types.

Any postulated deviations from a conformable sequence of, respectively, thick marble, gneiss, and thick marble involve seemingly untenable assumptions. Certainly no single fault or combination of faults reasonably consistent with the data would cause duplication or omission of a significant part of the section on a regional scale. The possibility has also been considered that the gneiss belt is now a closely folded isocline, either of synclinal or of anticlinal form. If this were true, the marble southeast of the gneiss belt, in the Balmat-Edwards-Russell areas (Figs. 1, 2), would be identical with that to the northwest which passes through the villages of Gouverneur and DeKalb. Via this assumption the gneiss could then be thought of as lying at the base, or top, of the Grenville series, rather than in the midst of the thick carbonate-rich facies.

This requires, however, that the gneiss form the core of the fold throughout the region and the flanks of the fold be flattened together, simulating integral parts of an unduplicated section. Further, we must assume that either the apex of this gigantic isocline in bedding parallels the earth's surface along the trace of the axial plane and has been destroyed by deformation or erosion, or the fold plunges into the earth and all relict bedding is so blurred at the apex that the fold remains undiscovered. These requirements seem extreme. A unique and improbable type of deformation and profound shearing out of sedimentary features are required to achieve this duplication of the gneiss throughout the 35-mile belt shown on Figure 2.

Other more specific objections are raised by the data derived from mapping at a scale of 800 feet to 1 inch throughout most of the belt of gneiss in the Gouverneur quadrangle, and in the marble southeast of the gneiss. The oldest folds observed in these marbles and in the gneiss (in relict beds) are those labeled A, B, C, D, on Figure 1. If the gneiss were duplicated in an isocline of regional dimensions, the formation of this great fold had to precede these lesser folds, for some of them involve the entire belt of gneiss as it now exists, as well as one or both adjoining marble belts. Undoubtedly the forces required to induce formation of a great regional isocline would also produce many subparallel, subsidiary folds and probably an associated axial-plane foliation in the bedding, or near the apex of the isocline.

The folding processes would tend to blur or obliterate bedding at the apex of the major fold, but locally, as on the flanks of the major fold, associated minor folds and some relicts of this axial-plane foliation should be preserved. These inferences seem especially valid in view of the many relict beds throughout the gneiss and marble. Refolding of the major fold and the minor ones, and of the associated axial-plane foliation and of related lineations, should also be visible along the axes of the known folds at A, B, and C (Fig. 1).

Evidence of such relict features has not been found. Some of the folds of the type at A, B, etc., lie at angles to, or directly athwart, the regional lithologic trend of gneiss and marble (Engel, 1949). In areas of these folds, the intersections of cleavages and bedding, as well as intersections of younger surfaces of cleavage, appear to be essentially parallel to each other and to the axes of all observed folds in both bedding, and in cleavages at any one point. There are no relict minor folds, or intersections of foliation distinctly discordant with the axes of cross folds. Certainly, in areas of cross folding, no visible relict secondary surfaces intersect the many widely scattered relict beds along lines trending northeast-southwest; nor have folded cleavages or folded intersections of cleavage and bedding been observed in areas of cross folding that might be "unfolded" into lines paralleling the axis of a nearly horizontal northeast- or southwest-trending regional isocline. These relations seem to support the con-

clusion that, in the surficial area of Figure 1, the gneiss is not repeated throughout its length by regional isoclinal folding.

The structural form and relations of the ellipsoidal body of quartz-biotite-garnet gneiss south of Edwards village (D, Fig. 1) are of considerable interest. Brown (1936, p. 241–242) concluded the gneiss was domical and a separate formation older than the main body of the gneiss to the northwest (Fig. 1); the two are separated by the Sylvia Lake-Edwards marble belt. The gneiss south of Edwards (hereafter the south Edwards segment) undoubtedly evolved from a thick sediment compositionally and texturally like the gneiss to the north and west. If Brown is correct, the Grenville series has two thick clastic units which are similar and, considering their intimate association with the thick marbles, of disturbing composition.

It seems unjustifiable, however, to assume that the south Edwards segment is either domical or a separate formation from the gneiss to the north and west.[1] Rather the south Edwards segment appears to represent a mashed anticlinal nose distended southwest from the major belt of gneiss; and, as will be discussed in a later section, the modest differences in bulk composition and textural features of this south Edwards segment from these features in the main gneiss belt may be related to differing environments of metamorphism.

Lithologic Features

General Statement

The observed rock types within the belt of gneiss between Antwerp and Hermon may be characterized briefly as gneiss, migmatite, and gneissic granite, although an extremely broad range of lithologic and chemical types exist. The "end members" of the predominant types are gneissic granite and quartz-biotite-oligoclase gneiss. In addition, thin layers of amphibolite and several zones of marble are intercalated in the gneiss.

Most of the amphibolite is a somewhat granitized hornblende-andesine rock, locally pyroxenic, in which biotite and chlorite appear as retrograde minerals. Many of the amphibolitic layers are only a few inches or a foot or two thick and are in sharp contact with the enclosing rock where it is not highly deformed. Although the aggregate volume of amphibolite interlayers and lenses is less than 10 per cent of the gneiss, they are widespread but of obscure origin.

The several marble interlayers are widely separated and highly deformed, commonly much thickened at the apices of large folds in the gneiss, and greatly thinned or parted at other places (Engel, 1949, p. 776–782, Fig. 9). Most marble interlayers are dolomitic with subsidiary siliceous interlayers. The siliceous layers have reacted with the dolomite to form diopsidic rock which has developed synchronously with, and is the facies analogue of, the quartz, biotite, and oligoclase in the gneiss and the hornblende and andesine in the amphibolite.

The segments of gneiss dominated by the assemblage quartz, a greenish-brown biotite, and oligoclase are almost certainly most representative of the nature of the parent sediment now entirely recrystallized and reconstituted. These layers are least complicated and altered by reaction and injection with granite magma in parts of the gneiss well removed both from the igneous massif of the central Adirondacks and from the larger bodies of more obviously intrusive granite in the Lowlands. Accordingly, some of the best relicts of unadulterated metasediment appear west of Hyatt (Fig. 4), in the segment of gneiss defined roughly between lines extending northwestward from Balmat Corners and west from Edwards village, hereafter referred to as the Hyatt sector. The essentially reconstituted (unadulterated) parts of the gneiss appear only as thin layers and lenses even in this and in other parts of the gneiss most isolated from the larger granitic intrusives. These layers and lenses are intimately interleaved and intertongued with pegmatite and granitic veins and sheets, and in many places blend by subtle transition into granitic augen gneiss and gneissic granite.

The typical migmatite or injection gneiss consists of layers of quartz-biotite-oligoclase

[1] A detailed map and discussion of the geological features in the Edwards area is in preparation as a publication of the U. S. Geological Survey.

gneiss, several inches to several or tens of feet thick, interlayered with quartz-potash-feldspar veinlets (Pl. 2). The gneiss layers are largely equigranular, fine-grained (Table 10), and faintly to distinctly foliated. The quartz-potash-feldspar (largely microcline) veinlets may be very coarse-grained or medium- to fine-grained.

The pegmatitic and granitic components are, in general, emplaced along the dominant foliation in the gneiss, although transgressive granitic bodies are common. The granitic veins appear as layers that may be paper thin or tens of feet thick. Some are quite uniform in thickness, but most pinch and swell abruptly, and many ellipsoidal lenses a few inches or a few feet thick are common. The lenses, too, are aligned along the foliation planes of the gneiss, which frequently tend to bulge outward around the introduced pegmatite.

Some ptygmatic veins of pegmatite and granite also appear in the gneiss. The contortions of these veins follow crenulated foliation surfaces at some places (Pl. 1), whereas elsewhere the ptygmatic veins cut across relict bedding, or the oldest visible foliation (Pl. 1).

Numerous examples of subtle transition between the dark-gray gneiss and gneissic granite (the Hermon type granite of Buddington, 1939, p. 142–145, 152–153, 161–168, 175–176; 1948, p. 3–43) have been noted in addition to and frequently in association with the well-defined pegmatitic and granitic veins. This granite is in considerable part gneiss more pervasively injected and replaced by granitic components. Many granitic phases of the gneiss are inequigranular with large augen of pink potash feldspar and locally of oligoclase (Pl. 2). Less-granitized phases of the gneiss, moreover, include pink, eye-shaped to subhedral crystals of potash feldspar (microcline) occasionally more than an inch in length.

Buddington (1948, p. 36–41) and others have suggested that this granitic rock, which is characteristically found associated with the gneiss in the Grenville Lowlands, is in large part of replacement origin. Buddington has attributed the granitic components to volatile-rich magma and fluids from this magma, which is satellitic to the magmas of certain of the great granite masses of the central massif (1948, p. 41–43). He has also argued that the geologic features indicate these far-travelled granitic components were emplaced at lower temperatures and pressures than those along and within the central Adirondack region (Buddington, 1939, especially p. 329–331). These hypotheses are consistent with and further substantiated by the data presented herein.

The Hyatt sector of gneiss, dominated by the simple assemblage of quartz, a greenish-brown biotite, and oligoclase—which seems to best reflect the composition of the parent sediment—coincides with the region of both lowest-temperature igneous phenomena and lowest-rank mineralogical facies in the Adirondacks. As the gneiss is traced north and northeast of Edwards into regions peripheral to the central Adirondack massif, new varieties of certain minerals, especially the biotite, may be observed, and other new minerals, particularly

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PLATE 1.—MIGMATITIC AND GARNETIFEROUS GNEISS

FIGURE 1. MIGMATITIC AND SLIGHTLY GARNETIFEROUS GNEISS

Crenulated pegmatite in part follows, and in part cuts across, the dominant foliation. The crumples are essentially ptygmatic types which show no systematic relationship to the major folds in the gneiss. They are interpreted as having formed during an appreciable decrease in thickness of the gneiss layers, which at this point were stretched in the direction of the foliation. The locality is approximately ¾ mile south of Balmat, N. Y. The scale at the base of the specimen is 6 inches long.

FIGURE 2. MIGMATITIC GNEISS

In an area where relatively straight, even layers merge into a zone of ptygmatic folds. The darker layers are quartz-biotite-feldspar gneiss, most of which ranges in composition between specimens 7 and 14 (Figs. 5, 6, 7). Lighter-colored layers of injection stuff are largely quartz-microcline rock with minor microperthite. In this exposure ptygmatic folds tend to follow the dominant foliation—which accords roughly with relict bedding—and are inferred to have formed through shearing off of the folded migmatite from the unfolded part, on the upper right part of the photo. The locality is about 1200 feet north-northeast of Fowler, N. Y.

FIGURE 1

FIGURE 2

MIGMATITIC AND GARNETIFEROUS GNEISS

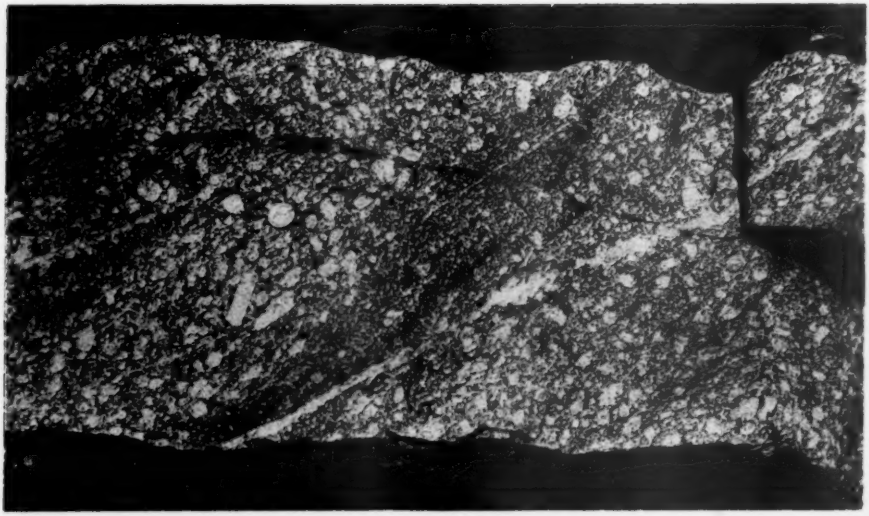

FIGURE 1

FIGURE 2

GNEISS

garnet and sillimanite, appear. These changes commonly accompany and are induced by the interaction of gneiss and magmas at higher temperatures. They also appear, however, in some parts of the gneiss that are relatively little altered chemically. Analogous changes occur as the gneiss is traced south of Edwards and south of Balmat. Of particular interest is a change in the color, composition, and optical properties of the biotite.

The succession of mineralogic and textural changes, and facies of the gneiss formed thereby are discussed below in order of increasing complexity and intensity of metamorphism and intrusion.

Least-Altered Gneiss

Texture.—In the Hyatt sector most of the layers of quartz-biotite gneiss that are least complicated by deformation are granoblastic. The foliation interpreted as relict bedding is widespread and moderately uniform, although never sharply defined. Layers of this type are locally sheared out into cataclastic to mylonitic zones. Some of these shear zones are massive, although more often they are strongly laminated or sheeted.

Other layers of the quartz-biotite-oligoclase gneiss are complexly swirled and blurred by discordant, secondary, or tertiary shears and foliations, some of which are about parallel to the axial planes of associated folds.

Mineralogy.—The dominant mineral assemblage composed of quartz, the greenish-brown biotite, and oligoclase commonly is accompanied by accessory sphene, apatite, chlorite, muscovite, sericite, pyrite, almandite, sillimanite, and magnetite. The proportions of the dominant minerals are remarkably constant in these layers of gneiss which appear from field and petrographic relations to be least injected or granitized—that is, merely reconstituted—and farthest removed from intrusive effects. The essential constancy of mineral composition in these stratigraphic relicts obtains irrespective of the stratigraphic position of the layer or its position along the strike of the gneiss complex in the area under discussion. This may be seen from the modes of typical specimens, which are assembled in Table 2. The distribution of some of these samples in the gneiss complex is shown in Figure 4. Most of the specimens are from the gneiss in the Hyatt sector. There the gneissic layers have a total thickness of at least 2800 feet, exclusive of obvious granitic veins and bodies. The specimens were chosen with reference to field relationships and without consideration of the modal composition. Many other specimens from sectors of gneiss to the northeast or southwest might have been added without appreciably modifying the implied composition. In general, the maximum variation of quartz in the specimens is only about 11 per cent (from 35 to 46 per cent); the average quartz content is 40 per cent in 35 of the least-altered specimens studied. Biotite ranges from 13 to 22 per cent and averages about 17 per cent; and oligoclase, or rarely andesine (An_{20-38}), ranges from 22 to 47 per cent and averages 39 per cent An_{26}. Typical accessory minerals are potash feldspar, muscovite, chlorite, apatite, pyrite, and magnetite. Garnet appears locally in the Hyatt sector as an accessory mineral. The garnetiferous specimens Qb-28 and Qb-38 (Table 2) are from the area farther northeast (Fig. 4).

Chemical composition.—The general uniform-

PLATE 2.—GNEISS

FIGURE 1. INEQUIGRANULAR GRANITIC GNEISS

The large anhedral to locally almost euhedral grains are salmon-pink microcline. These are formed by replacement of the groundmass which now has the approximate composition of specimen 18 (Figs. 5, 6, 7 and Table 5). Note the quarter of a dollar for scale.

FIGURE 2. ONE TYPE OF SILLIMANITIC AND GARNETIFEROUS GNEISS

Much of the sillimanite occurs in the knots and stretched clots, along with quartz and sericite. These clots have their longest dimension essentially parallel to the axes of associated large folds in the gneiss. The dark layer in the center of the photo is highly garnetiferous pegmatite.

TABLE 2.—APPROXIMATE MINERAL COMPOSITION OF LAYERS ASSUMED TO BE LITTLE ADULTERATED METASEDIMENT (GNEISS)

Most specimens are from the Hyatt sector and from north and northwest of Edwards, New York.

Specimen number	Qb72	QbB	Qb12	Qb59	Q12U	QbE	Qb51	Qb25	Qb58	Qb41	Qb1	Qb28	Qb5W	Qb38	Qb21	Av. Comp.
Quartz	35	36	37	38	39	39	39	40	40	40	40	44	45	46	46	40
Plagioclase, commonly oligoclase or oligoclase-andesine	43	47	45	42	44	46	35	45	39	38	37	38	22	36	39	39
Potash feldspar commonly orthoclase	2	1	1	1	3*	1	3	1*	1	1	2	1	1	1	1	1
Biotite (greenish-brown)	18	16†	17	19	14	15	21	14†	20	20	22	15†	22	13	14†	17
Garnet	1											3		4		

* Microcline.

† Reddish brown biotite.

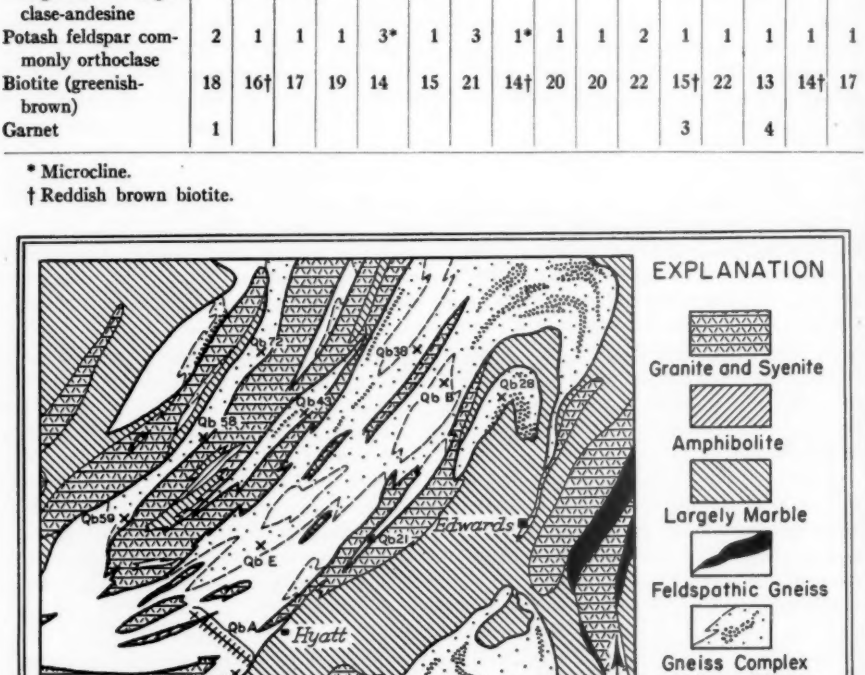

FIGURE 4. SKETCH MAP OF THE HYATT SECTOR AND ADJACENT PARTS OF THE GNEISS COMPLEX

Showing the distribution of many specimens referred to in the text, as well as highly generalized garnet and sillimanite isograds.

ity in composition of gneiss that seems to be little-adulterated or granitized metasediment is as strikingly attested by chemical analyses of these layers. In Table 3, for example, analyses QbA, Qb2, and 4537 are of these layers of quartz-biotite-oligoclase gneiss. QbA is a composite analysis of 14 least-injected, granitized, and deformed layers thought to be relict beds which appear at intervals in a section 1500 feet thick, west of Hyatt, New York (Fig. 4). Qb2 is an analysis of a single, typical layer, near the base of this section. Specimen

4537 was collected and analyzed by Buddington (Smyth and Buddington, 1926, p. 20) in an earlier independent attempt to determine the composition of the least-adulterated metasediment. This specimen comes from the gneiss southwest of Balmat, 6 miles from QbA and Qb2.

The three analyses are remarkably similar. The analyses QbA and Qb2 are so nearly identical and in certain ways peculiar as unaltered metasediment associated with marble as to be suspect. Accordingly the outcrops were resampled at the same localities, and partial analyses rerun in the laboratories of the U. S. Geological Survey as shown by Qb2A, Table 3. There can be no doubt of the similarity in composition of the composite and single samples. None of the major oxides in the initial and partial analyses of the composite sample differs from that in the analyses of the single specimen by more than 0.6 weight per cent.

In addition there is remarkable agreement of these analyses with that made by Buddington (4537, Table 3). Unfortunately none of Buddington's specimen 4537 is left for further study, but he notes (written communication) that the specimen may have been slightly granitized. This is consistent with the slightly lower values of FeO, Fe_2O_3, MgO, and Na_2O and the decrease in the ratio of Na_2O to K_2O. These are typical although incipient changes which, as shown later, are characteristic of the granitized gneiss. Even assuming no metasomatic changes in this specimen, it is remarkably similar in composition to and has the same unique aspects as the other specimens of quartz-biotite-oligoclase gneiss. Furthermore, the mineralogical composition of least-altered gneiss throughout the area of Figure 1 indicates a similar bulk chemistry and lithology. The conclusion is almost inescapable that the gneiss formation in the northwest Adirondacks was almost monotonously uniform in composition prior to injection and granitization. This same monotony persists in the texture and general appearance of the layers.

As noted in Part I, the bulk chemistry of the layers assumed to be least altered certainly is not that of a conventional shale, although it approaches very closely that of many graywackes and some dacitic tuffs. These sedimentary types are not to be expected conformably interlayered with marbles, however, and the question is raised whether the rather high ratio of Na_2O to K_2O may reflect large-scale abstraction of K_2O or conversely the addition of Na_2O. These problems are elaborated under the heading Origin of the Gneiss.

TABLE 3.—CHEMICAL COMPOSITIONS IN WEIGHT PER CENT OF ROCKS ASSUMED TO BE ESSENTIALLY UNALTERED SEDIMENT NOW RECONSTITUTED INTO GNEISS

Specimen number	QbA	Qb2	Qb2A (recheck)	4537
SiO_2	70.90	70.50		71.00
Al_2O_3	12.17	12.44	13.01	14.00
Fe_2O_3	1.31	1.57	5.58	0.55
FeO	4.12	3.92		3.16
MgO	2.32	2.27	2.25	1.26
CaO	1.55	2.13	2.04	2.26
Na_2O	3.74	3.57		3.20
K_2O	2.87	2.56		2.70
H_2O+	0.21	0.27		0.61
H_2O-	0.05	0.02		0.09
TiO_2	0.32	0.32	0.66	0.53
MnO	0.04	0.06		0.05
P_2O_5	—	—		0.10
Totals	99.60	99.63		99.50

QbA Composite sample of 24 specimens of apparently least altered gneiss collected along a traverse of 2000 feet, at right angles to the strike of the gneiss, from the West Branch, Oswegatchie River, north to the Main Branch. 0.8 mile southwest of Hyatt (Fig. 4). Analyst, Ledoux and Company.

Qb2 An essentially uninjected and unaltered layer of quartz-biotite-oligoclase gneiss near the southern end of the traverse noted in QbA. About 0.8 mile southwest of Hyatt, New York. Analyst, Ledoux and Company.

Qb2A Analysis of second set of samples taken from the same exposures as Qb2. Analyst, Leonard Shapiro, U. S. Geological Survey.

4537 Least granitized and altered layer of quartz-biotite-oligoclase gneiss, 2 miles west of Balmat, New York. Analyst, A. F. Buddington. (From Smyth and Buddington, 1926, p. 20.)

Features reflecting metamorphic rank.—The ubiquity of the assemblage quartz, greenish-brown biotite, and oligoclase as the oldest visible metamorphic assemblage is also noteworthy. There are no clearly defined antecedent

or relict minerals to suggest a preceding step or stage of lower-grade metamorphism.

The chlorite as well as some of the sericite and albite recorded as minor constituents are equilibrium with the quartz, biotite, and oligoclase.

The greenish-brown biotite appears in nearly all the least-granitized specimens from the

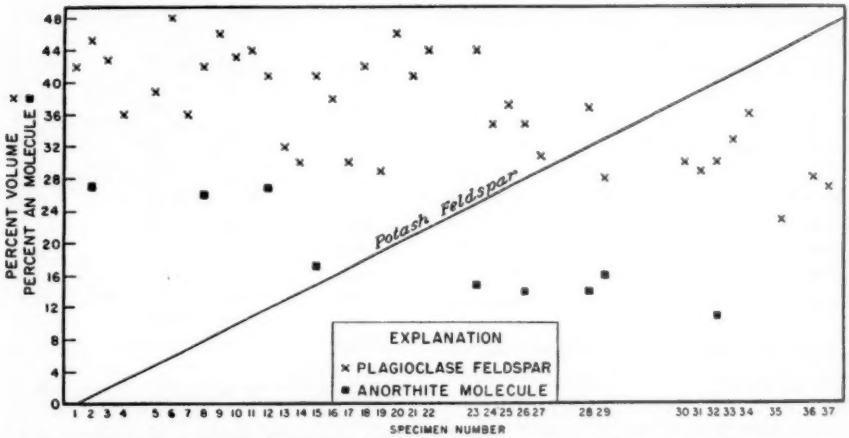

FIGURE 5. PERCENTAGE OF ANORTHITE MOLECULE AND AMOUNT OF PLAGIOCLASE FELDSPAR IN SPECIMENS OF THE GNEISS-GRANITE COMPLEX OF THE HYATT SECTOR PLOTTED AGAINST INCREASING POTASH FELDSPAR CONTENT

Each specimen is actually an average of two specimens collected from separated parts of the gneiss. This figure contains the same specimens, in the same order, as Figure 6 in which the amounts of biotite and quartz have been plotted. The data from these two figures are summarized in the form of curves in Figure 7 and interrelated to textural and chemical changes during successive stages of interaction of gneiss and granite.

products of a superimposed retrograde metamorphism which is only locally conspicuous. Thus, along marked breccia and shear zones, the biotite may be largely replaced by chlorite, and the oligoclase may be highly sericitized, or partly replaced by albite. Incipient examples of these changes also appear in many of the least-deformed layers. Some additional albite in the form of rims to the oligoclase also appears to be produced during granitization but prior to retrograde processes.

If the formation of the assemblage quartz, greenish-brown biotite, and oligoclase climaxed a sequence of progressive metamorphism, with the evolution of chlorite, albite, and other minerals at earlier stages, as is commonly observed in the metamorphism of rather similar clastic sediments from other terranes (*see, for example*, Turner, 1948, p. 35–39) no evidence of a preceding step remains.

Some muscovite in the gneiss, however, rarely in excess of 5 per cent, has formed in Hyatt sector. The greenish tinge characterizes biotite in these least-injected and metasomatized layers of gneiss, particularly where they appear best preserved from the effects of the higher-temperature igneous and metamorphic phenomena. Some reddish-brown biotite, commonly with slightly lower index, also appears, however, even where the gneiss is farthest from the central Adirondack massif; but, as is shown in the section on Significant Variations in Mineral Species, 80 per cent of the examples of reddish-brown biotite found in the Hyatt and other outlying sectors is associated with the more extensively granitized and migmatized parts of the complex.

Injected and Altered Gneiss

Textural, mineralogical, and chemical changes.—The general textural, mineralogical, and chemical changes accompanying the evolution of migmatite and granite from gneiss in the Hyatt sector are plotted in Figures 5, 6, and

7 and Table 4. Although a relatively small part of the more alkalic "granite" is almost surely a deformed igneous rock, nearly the entire range of composition in these tables is also interpreted as having formed via replacement of gneiss by magmatic fluids or interaction with them. Consequently, these tables show not only the various kinds of true injection gneiss and magma type but, in addition, the range in compositions induced by replacement and reciprocal reaction.

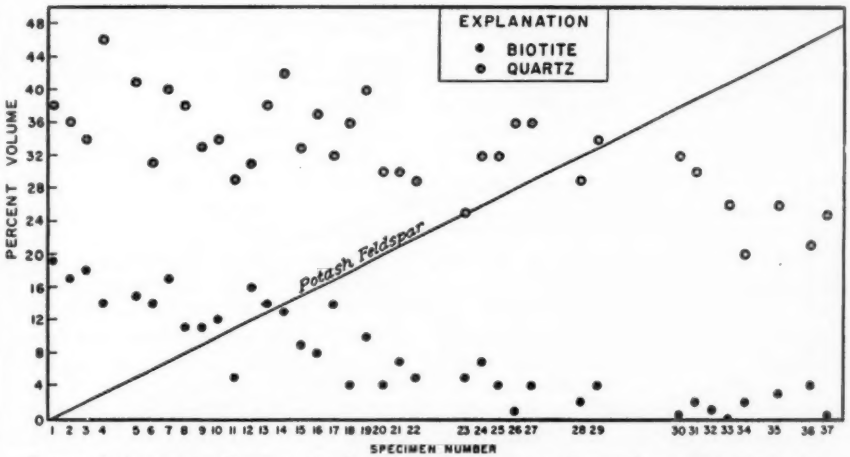

FIGURE 6. AMOUNT OF BIOTITE AND QUARTZ IN SPECIMENS OF GNEISS-GRANITE COMPLEX OF THE HYATT SECTOR PLOTTED AGAINST INCREASING POTASH FELDSPAR CONTENT

This figure contains the same specimens, in the same order as Figure 5, in which the amounts of plagioclase and the per cent anorthite molecule have been plotted. Each "specimen" is actually an average of two specimens collected from separated parts of the gneiss.

The mineralogical data from these two figures are summarized in the form of curves in Figure 7 and interrelated to textural and chemical changes during successive stages of interaction of gneiss and granite.

Figures 5 and 6 show the successive modifications in the mineralogical composition and in the per cent anorthite in the plagioclase feldspar. Modal compositions of specimens of gneiss, each more injected and feldspathized than the preceding, are plotted against an increase in potash feldspar (chiefly microcline). All these changes are shown as generalized curves in Figure 7 with the paralleling modifications in textural features in the gneiss complex, which have been tabulated from field data. The average compositions of gneiss and inequigranular granite (specimen numbers 13 and 25 respectively) are also indicated, as are the approximate positions in terms of composition and texture, of the arbitrarily designated boundaries between gneiss and granite. In Table 4 are tabulated five chemical analyses of which the specimens Qb2, Qb11, PG18, EG28 appear on Figures 5, 6, and 7. The chemical changes which accompany the mineralogical and textural transformations are apparent from these analyses.

The mineralogical changes which accompany the progressive increase in potash feldspar clearly include (1) a decrease in quartz from roughly 40 per cent in the least-altered gneiss to less than 25 per cent in some facies of the granites, (2) a decrease in biotite from approximately 18 or 20 per cent to several per cent, and (3) a decrease in the volume of plagioclase and in its anorthite content. The plagioclase in what is inferred to be the reconstituted gneiss (Table 2; Figs. 5, 6, 7, specimens 1 and 2) averages about Ab_{74} and constitutes 42 to 45 per cent of the rock. In contrast, those specimens of the gneiss complex which are interpreted as most modified by interaction with, or replacement by, granitic fluids contain either sodic oligoclase or calcic albite which constitutes less than 30 per cent of the

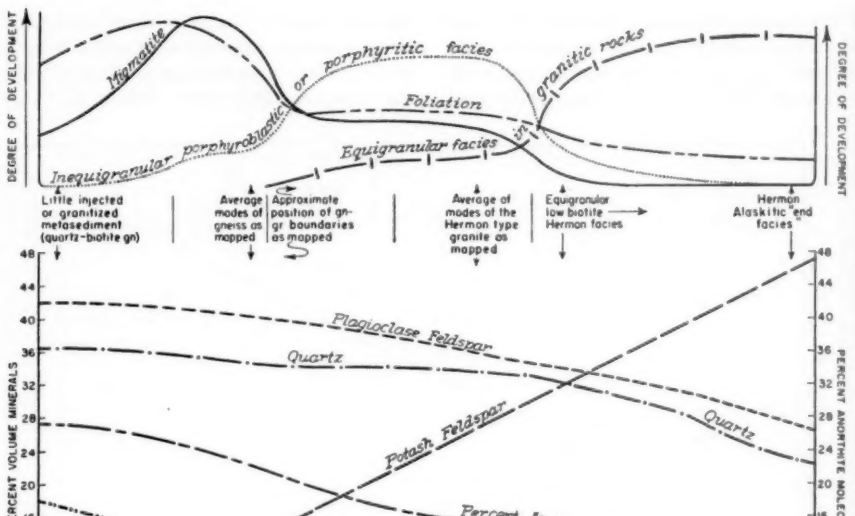

FIGURE 7. GENERALIZED CURVES SHOWING THE INTERRELATIONS BETWEEN THE MINERALOGICAL, CHEMICAL, AND TEXTURAL EVOLUTION OF THE GNEISS COMPLEX

The lower set of curves, which indicate changes in mineralogical composition, are drawn from the data in Figures 5 and 6. Corresponding variations in texture are plotted in the upper diagram. The bulk compositions of the four indicated specimens from which chemical analyses have been made are given in Table 4 as Qb-2, Qb-11, PG-18, and EG-28, in the same order shown above. Note that the approximate positions of the boundaries of "gneiss" and "granite" as plotted on the maps are also indicated, as well as the "average" compositions of these units.

total volume. The decrease in biotite is most uniform and consistent in the larger areas of pervasively granitized and injected gneiss, whereas a local type, high in biotite and high in potash feldspar, appears as interlayers in dominantly migmatitic rock.

The curves that indicate textural modifications in the gneiss complex accompanying changes in composition (top of Fig. 7) show the common fields of occurrence of migmatitic, inequigranular, and equigranular facies as well as two distinctive breaks in textural types. The migmatitic types characterize the incipiently to moderately feldspathized and injected gneiss complex although some gneiss with this range of composition has been altered by uniform, pervasive types of replacement. The intermediate stages in the alteration of the gneiss are dominated by porphyroblastic facies. Plate 2 shows one type. In most of the more extensively granitized rock, however, or in what may well be largely igneous facies (as indicated by the specimens on the right side of Figs. 5, 6, and 7) nearly equigranular types are characteristic.

The break in textural features on the left between migmatite and less distinctly layered inequigranular granitic gneiss has been utilized as the best practical point of distinction in the field. Rock types texturally and compositionally left of this "break" (roughly 15 to 16, Fig. 7) are mapped as gneiss. The granitic rock to the

right of say 16, (Fig. 7) and various subtle blendings of more alkalic but texturally similar rocks, are fairly typical and have been mapped as the Hermon type inequigranular granite complex. Perhaps the major exceptions to this generalization appear in zones in the northwesterly side (base?) of the gneiss and in its more easterly extent at and near the Adirondack Upland. There the mineralogical and chemical changes are consonant with those plotted in Figure 7, but the curves indicating textural and lithologic changes show much less abrupt breaks in the area of, for example, specimen 16 than do those in Figures 5, 6, and 7. That is, very subtle blendings and extremely intimate interlayerings of gneiss and granite are far more common. These blendings and interlayerings are almost impossible to map at scales smaller than 10 or 25 feet to 1 inch. If this northwesterly part of the gneiss does represent the base of an anticlinorial arch, these layers were ideally situated to undergo the more thorough and pervasive alteration. This is true even if the layers were no more, or somewhat less, amenable to alteration than those in the overlying gneiss.

The inequigranularity characteristic of the Hermon granitic types is produced by the appearance of large, in many instances sieved, potash feldspars (largely microcline) in the gneiss (Pl. 2). Some of these microclines tend to be subhedral to euhedral, the faint foliation in the gneiss abuts against their ends, and they appear to have formed by replacement of the gneiss during its deformation. Others are, however, eye-shaped, the layers of gneiss bend around them, and they may have formed by forcing apart the gneiss folia. Within the more granitic Hermon gneisses (right center of Fig. 7), some of these large potash feldspar individuals also could be phenocrysts grown in magma as it permeated or shredded and interacted with leaves and lenses of the gneissic metasediment. Examples, which may be of this type, appear in rocks whose composition commonly lies in about the area of the "average Hermon type granite" (Fig. 7). In this compositional and textural range we find no clean-cut criteria for distinguishing between the amounts of magmatic and metasomatic granite in the outcrop.

The analysis of specimen 28 (Fig. 7) seems, however, to represent about the most granitic (alkalic) facies that is readily inferred to have formed over large areas by replacement of gneiss. This composition is roughly coincident with the textural break between the inequigranular, biotitic, Hermon type granite and uniform-grained, almost alaskitic granite (Fig. 7). A number of other features suggest that the facies to the right of 28 is dominantly igneous in origin, although there is clearly no unequivocal basis for such a conclusion.

In this area of textural change, as in the vicinity of the break between migmatite and inequigranular Hermon type granite, some examples of granitic gneiss fall texturally on one side of 28, but compositionally on the other side of this point. These examples are also a small minority which appear most frequently along the northwest side (base) of the gneiss, and at and near the Adirondack massif.

The chemical analyses of the specimens 2, 11, 18, and 28, whose positions are recorded in Figure 7, are tabulated in Table 4. As is implied by the mineralogic changes, successive stages in the injection and granitization of gneiss involve a marked increase in alkalis, especially potash, and a marked diminution in magnesia, iron, and lime. The essentially unaltered metasedimentary layers (QbA and specimen Qb2) are volumetrically small as compared with those compositional and textural types near the "average of 58 modes of gneiss as mapped" (13, Fig. 7).

A feature of considerable interest in the chemical data is the change in the ratio of Na_2O to K_2O with successive stages of granitization. The distinctive, initial preponderance of Na_2O over K_2O (approaching 3:2) is overcome in the intermediate types, and ultimately the K_2O content of the evolving rock may be doubled or tripled, and exceeds the Na_2O content. Although the total Na_2O content is also increased, the increment is rarely more than 20 to 30 per cent by weight. The granitizing effects tend to alter the composition toward a type somewhat more "normal" for either a common shale, siltstone, or igneous rock. These relations of the alkalis appear to have great significance in any consideration of the origin

TABLE 4.—CHEMICAL ANALYSES AND MODES OF GNEISS, GRANITIC GNEISS, AND HERMON TYPE GRANITE

Specimen number	Qb-A	Qb-2	Qb-11	PG-18	EG-28
SiO_2	70.90	70.50	64.18	72.35	69.40
Al_2O_3	12.17	12.44	16.19	12.94	15.63
Fe_2O_3	1.31	1.57	1.87	1.13	0.60
FeO	4.12	3.92	3.98	1.52	0.62
MgO	2.32	2.27	2.17	0.72	0.14
CaO	1.55	2.13	2.69	1.33	0.18
Na_2O	3.74	3.57	4.64	4.22	5.03
K_2O	2.87	2.56	3.48	4.90	7.73
H_2O+	0.21	0.27	0.24	0.18	0.18
H_2O-	0.05	0.02	0.06	0.05	0.04
TiO_2	0.32	0.32	0.34	0.10	0.04
MnO	0.04	0.06	0.06	0.03	trace
Total	99.60	99.63	99.90	99.51	99.58

Modes

	Qb-2	Qb-11	PG-18	EG-28
Quartz	40	29	36	29
Plagioclase	37(Ab^{73})	44(Ab^{75})	42(Ab^{82})	37(Ab^{88})
Biotite	20	15	4	2
Potash feldspar	1	11	18	31
Magnetite, apatite, zircon, pyrite, tourmaline	1±	1±	1±	1±

Qb-A. Composite sample of 24 specimens of least altered gneiss collected along a traverse of 2000 feet at right angles to the strike of the gneiss, from the West Branch, Oswegatchie River, north to Main Branch. Area is 0.8 mile southwest of Hyatt (Fig. 4). Ledoux and Co., analysts.

Qb-2. An essentially uninjected and unaltered layer of quartz-biotite-oligoclase gneiss near the southern end of the traverse noted in description of Qb-A. About 0.8 mile southwest of Hyatt, N. Y. Ledoux and Co., analysts.

Qb-11. Porphyroblastic facies of Hermon type granite, from gneiss complex northwest of Hyatt. Ledoux and Co., analysts.

PG-18. Porphyroblastic facies of Hermon type granite, north of Hyatt. Ledoux and Co., analysts.

EG-28. Alaskitic granite in gneiss northeast of Hyatt. Ledoux and Co., analysts.

and evolution of the gneiss and are considered in detail in a succeeding section.

One other noteworthy feature of the progressive changes in the gneiss complex is that the sequence as plotted via mineral or direct chemical composition may appear in the gneiss on scales of several feet or several thousands of feet. That is, the transition from gneiss to granite may be relatively abrupt or extremely gradual and subtle. Owing to the uniformity in composition of the parent metasediment and the pervasive nature of the changes at some places, the same trends also may appear across as well as along the strike. In addition, many thin sheets of granitic rock such as represented by, say, specimens 18 or 28 (Figs. 5, 6, 7; Table 4) are sharply interlayered with gneiss which approaches in composition the least-injected specimens such as 2. Perhaps it is well to re-emphasize that the granitic components are in part confined to discrete injection layers, and in part are more pervasively distributed in the gneiss, and that both types appear in most large segments of the gneiss.

Significant variations in mineral species.—The variations in properties of the biotites in the gneiss and the appearance of garnet and sillimanite in the migmatite are significant as-

pects of the evolution of these rocks. Smyth and Buddington (1926, p. 18–19) apparently first noted that most of the biotite in certain segments of the gneiss in the Grenville Lowlands had a distinctive, greenish tinge. Subsequently Gilluly (1936, p. 9–21) studied the gneiss between Balmat and Edwards and noted that about half the specimens he collected contained the greenish-brown biotite and half had the reddish-brown variety. He also found several specimens of gneiss that contained both varieties of biotite. Gilluly speculated that the reddish-brown variety "either was introduced or is in the product of metamorphism of the greenish-brown biotite by emanations from the impregnating granites" (1936, p. 14).

Gilluly's second alternative is in large part consistent with the present data, although the changes noted in the biotite also seem to be induced by simple reconstitution in parts of the gneiss metamorphosed at relatively higher temperatures. As Tilley (1926), Harker (1932, p. 214–217), and others have noted, varieties of biotite including types much like these in the gneiss may appear as successive products during what seems to be a more strictly dynamothermal or "regional" metamorphism. Ambrose (1936, p. 257–286) noted the evolution of first a greenish, then a reddish biotite in successively more highly metamorphosed graywackes of the Missi series near Flinflon, Manitoba. The instance has special pertinence in that the mineralogical facies of quartz, oligoclase, and mica, with garnet, suggests a parent metasediment of almost the same bulk chemistry as the unadulterated gneiss. Ambrose (1936, p. 257) concluded that the differences in the biotite were induced by thermal metamorphism and that the heat was developed mechanically by and during intimate internal shearing; further that "neither proximity to an igneous mass nor depth of burial can be held to account for the advance in metamorphic rank of the various rocks."

Sugi (1935, p. 138–143) describes a reddish-brown biotite and a greenish-brown variety in metasediments and migmatites of northeastern Japan. There the bulk chemistry of the several rock types approximates the gneiss and certain of its migmatitic facies. Sugi also notes that the reddish-brown biotite occurs in the more highly metamorphosed facies, with oligoclase and some garnet. These minerals are evolved, however, in conjunction with migmatization of the metasediment, and Sugi suggests that a mutual reaction of metasediment and granitic components was instrumental in the evolution of the reddish-brown biotite, as well as garnet and sillimanite. The rock types described by Sugi appear to parallel very closely those observed in most parts of the gneiss, and the inferred metamorphic processes are much the same.

Some indication of the relations of the greenish to reddish biotite upon injection and feldspathization of the gneiss in the Hyatt sector is obtained from the data in Figure 8. There are plotted the per cent by volume of biotite and potash feldspar in 46 typical specimens from the Hyatt sector. These specimens were obtained from points as widely and uniformly spaced as possible along and across the strike in an area of about 10 square miles. They include examples of least-injected gneiss, intermediate types, and more highly altered gneiss.

The associations seem clear. Reddish-brown biotite appears in the injected and granitized specimens; the greenish-brown variety predominates in the least-altered facies. Thus 24 of the 46 specimens of gneiss contain greenish-brown biotite, and of these only 3 contain more than 10 per cent potash feldspar. In contrast, of the 22 specimens containing reddish-brown biotite, only 2 contain less than 10 per cent potash feldspar.

The specimens included in Figure 8 are only the more equigranular rocks, in which the percentages of feldspars and biotite could be more precisely approximated by modal analyses. The same general relations exist, however, in the more inequigranular facies of migmatite mapped as gneiss—that is, where the more granitic types as represented by the compositions on the center and right side of Figure 7 are not extensively developed. Almost invariably the biotite in the least-adulterated layers is greenish brown, whereas much of that along granitic seams, where there has been obvious interaction of gneiss and granite, is reddish brown.

The variations in index of refraction of 25 greenish-brown and reddish-brown biotites are

plotted in Figure 9. In the greenish biotites of the Hyatt and near-by areas, the γ index ranges from 1.640 to 1.656 averaging about 1.646; in the reddish-brown variety of the adjacent area north of Edwards, the γ index ranges from 1.638 to 1.650 averaging about 1.641. In both types, a perceptible increase in 2V commonly parallels an increase in index of refraction. Consequently most of the greenish-brown varieties tend to have somewhat larger 2V than most of the reddish-brown varieties from the area north of Edwards. The reddish-brown biotites from the south Edwards area, however, show wide variations in index of refraction, with values of the γ index ranging from 1.636 to 1.653. In these biotites changes in size of 2V appear to be grossly related to changes in index; the specimens with the high-

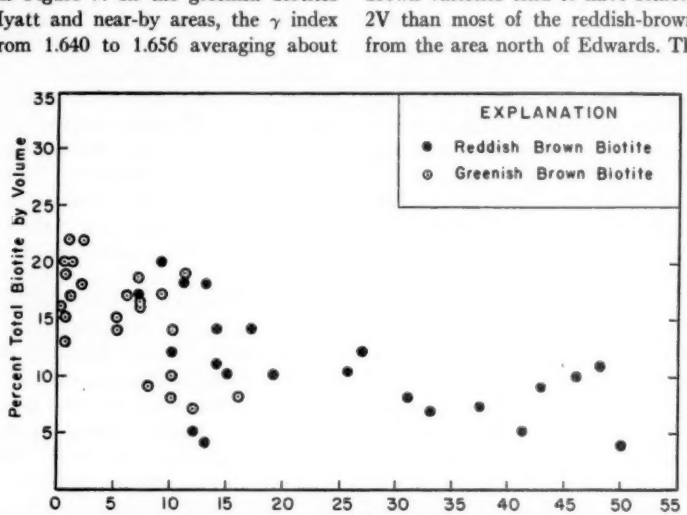

FIGURE 8. RELATIONS OF THE BIOTITES IN THE GNEISS COMPLEX TO CONTENT OF POTASH FELDSPAR

The reddish brown biotite has formed at the expense of the greenish variety largely in conjunction with the interaction of gneiss and potash rich magmatic fluids.

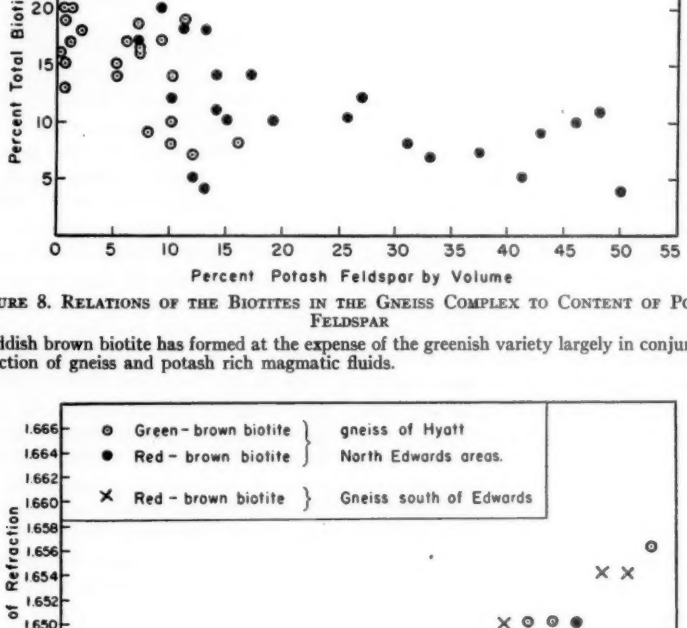

FIGURE 9. VARIETIES OF GREENISH-BROWN AND REDDISH-BROWN BIOTITE PLOTTED IN ORDER OF INCREASING γ INDEX

est index exhibit the largest 2V. Data are insufficient to relate these changes in index and color to chemical composition. Commonly the change in color of metamorphic biotites from greenish brown to reddish brown is thought to reflect an increase in FeO (Barth, 1936, p. 182), but Hall (1941) and Heinrich (1946) note some of the difficulties of predicting composition in biotites from their color or index of refraction. Hall concludes that in most instances greenish-brown biotites reflect either high FeO + low TiO + low MgO or low FeO + low TiO_2 + high MgO. The problem of the biotites in the adirondack gneiss is complicated by the fact that the greenish-brown biotites appear to have a somewhat higher average γ index than the reddish-brown biotites along the strike, apparently a reversal of the relations commonly described. The writers are studying these biotites more thoroughly in an attempt to relate their physical and chemical properties to other phenomena in the gneiss.

The fairly constant association of greenish biotite in least-injected gneiss and the reddish variety in the more migmatitic types might suggest that the biotite in the larger and more extensively granitized rock—the segments mapped as Hermon Type granite—is the reddish variety. Actually these larger granitic bodies in the Hyatt sector contain both varieties although the reddish-brown biotite is slightly predominant in most places. The relations seem most consistent with the concept that the incipient or early stage of injection and interaction of gneiss by granitic components was accompanied by a change from greenish to reddish biotite at the sites of granitic emplacement; whereas more extensive development of granite either was not accompanied by the further alteration of the biotite, or, less probably, the reddish biotite formed but has been realtered to the greenish variety.

Infrequently, certain exceptions are noted to these trends of migmatization and granitization as tabulated above. For example, a few scattered layers of potash feldspar-rich gneiss are abnormally high in biotite, even for the unadulterated gneiss. These more biotitic layers, such as Qbc (Table 7) from the Hyatt sector, are of local extent and clearly transgress and postdate the relict beds of least-altered gneiss. They tend to be blurred or obliterated, however, by the normal trends of the reciprocal reaction between gneiss and granite. They thus seem to be quantitatively unimportant and formed only in the early stages of granitic emplacement. The other examples in Table 7 are from garnetiferous and sillimanitic sectors of the gneiss and will be referred to later. All are closely associated with granitic rock and contain the reddish-brown biotite.

One obvious although difficultly proven explanation of these abnormally biotitic and microcline-rich layers is that they represent basic fronts formed under the influence of mafic emanations themselves expelled from granitized gneiss, either near by or at depth. An equally reasonable alternative is that some of the excess iron as well as alkalis of this high-biotite, high-potash feldspar phase of the gneiss were derived from granitic magma or from magmatic fluids. Certainly there are what seem to be well-defined examples of mafic, pyrometasomatic assemblages in the marbles interlayered with the gneiss. There, sphene- and scapolite-rich amphibolites, having the bulk chemistry of mafic igneous rocks, are formed by skarnlike metasomatism of siliceous dolomite and low-iron diopsidic layers (Buddington, 1939, p. 11–14, 161, 168–173; Engel and Engel, 1952).

Some of these amphibolitic rocks occur as interlayers in gneiss and marble, and, although well removed from an obvious igneous body of significant dimensions, they are relatively rich in F, Cl, P, and other components suggestive of a magmatic source. Others have evolved as pyrometasomatic sheaths or aureoles to the phacolithic and other granitic intrusions, and the association of mafic metasomate and granite is constant and compelling (Buddington, 1929). Both these types seem, in the light of regional studies, to be the lower-temperature, Grenville Lowland analogues of the magnetite-bearing skarns found near Star Lake, Degrasse, and elsewhere (Newland, 1908; Leonard, 1951).

In all these examples the early stages of iron fixation are followed by stages—the dominant course apparent in the gneiss proper—wherein any early-formed mafic assemblages are grani-

tized with a concomitant depletion in iron, magnesia, and lime.

The course of this granitization of the amphibolites in the gneiss parallels in time the trends of change in the gneiss as discussed above. Many of the amphibolitic interlayers are converted into quartz-biotite-feldspar gneisses and chloritic schists. Buddington (1939, p. 161) notes the evolution of garnet-sillimanite schists and quartz-feldspar gneisses in the amphibolitic contact aureoles around granites, and Leonard (1951, p. 168) describes modifications including quartz, potash feldspar, fluorite, barite, and very locally scapolite or spessartite in the commercial magnetite-bearing skarns.

We see no criteria by which to differentiate any abnormally biotitic segments of gneiss evolved from basic fronts from those which may be formed through interaction of magmatic fluids directly upon gneiss. The basic front concept is perhaps most appealing if evidence from the gneiss alone is considered. But the implications of regional studies are that volatile-rich mafic-bearing fluids were expelled from certain of the granitic magmas into the enveloping Grenville series. Iron-rich replacements formed by these fluids are widely distributed, especially in the carbonate rocks associated with the gneiss. It is an almost inescapable conclusion that they traversed parts of the gneiss and locally and temporarily may have augmented the concentrations of iron and titania therein.

The very local occurrence of garnet and sillimanite in the Hyatt sector of gneiss is clearly associated with that of reddish biotite and with the first significant generations of granitic interlayers. The association of garnet and the pegmatite veinlets in the gneiss was noted first by Buddington (1934, p. 116) who subsequently (1939, p. 175) concluded:

> "... the pegmatite, where injected, has developed the garnets by incorporation of material of the country rock (primarily biotite) and reaction with it and that, where of replacement origin, the garnet developed contemporaneous with the pegmatite formation."

This is undoubtedly correct in most areas of gneiss. There are, to be sure, examples of garnetiferous gneiss which contain very little injection material, and occurrences of injection gneiss in which the garnets occur within the gneissic layers as well as in or along the pegmatitic seams, but these garnets are a small minority, and the areas of gneiss in which they occur are limited in size and number. They coincide largely with segments of the gneiss nearest the central igneous massif or near obviously intrusive granite where relatively high-rank reconstitution of the gneiss has occurred. At least three-fourths of all garnets in the gneiss appear within or along the more obvious layers and lenses of pegmatite, or granitized gneiss.

Moreover, most of the garnetiferous layers of gneiss—and all that are appreciably granitized in the Hyatt sector—are associated with the reddish biotite. These relations are shown in Figure 10 where the 23 examples of garnetiferous gneiss from the Hyatt sector are plotted by amount and kind of biotite against per cent by volume of potash feldspar. The five specimens of gneiss in which garnet has been found associated with greenish-brown biotite all contain less than 6 per cent potash feldspar.

The associations of reddish biotite with garnet raise the question whether the red color of the biotites may be induced by their depletion in ferrous iron and enrichment in magnesia. Some almandite-rich garnets which form in metamorphic terranes preferentially fix ferrous iron over magnesia (Barth, 1936, p. 782). This is because the FeO in the garnet is not isomorphously replaced by MgO. If this were true in the gneiss, the ratio of ferrous iron to magnesia in the biotite would drop as the garnets formed. Inspection of the analyses of the garnet from the north Edwards area shows 6.49 weight per cent MgO however and only 29.43 per cent FeO, indicating that any enrichment of the associated biotites in MgO has not been great.[2] Whether changes of this type actually have caused the appearance of reddish colors in the biotites may be determined only with additional analytical data on both garnet and biotite.

The garnets in the Hyatt area have never been analyzed although their index of refraction shows little variation from about 1.795, which is very close to that (1.799 ± .003) of

[2] Almandite garnets formed with biotites in other terranes contain as little as 1.7 to 2.3 MgO and 32.4 to 36.7 FeO (Barth, 1936, p. 782).

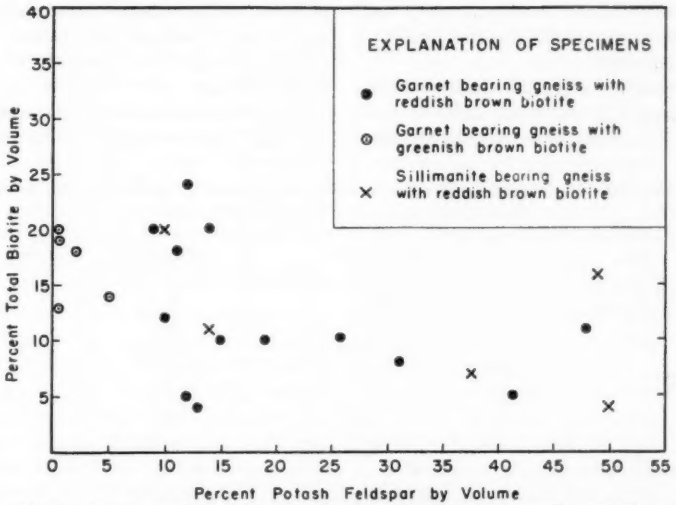

FIGURE 10. RELATIONS OF GARNET AND SILLIMANITE TO BIOTITES AND POTASH FELDSPAR IN THE GNEISS COMPLEX OF THE HYATT SECTOR

Garnet and sillimanite appear only locally, and in the order named, with increasing interaction of gneiss and granite, presumably at relatively higher temperatures.

TABLE 5.—CHEMICAL ANALYSIS IN WEIGHT PER CENT OF PINKISH-RED GARNET FROM THE NORTH EDWARDS AREA

Index of refraction of the garnet is 1.799 (±.003). The locality is approximately 1¼ miles north of Edwards village. Eileen K. Oslund, analyst.

SiO_2	38.03
Al_2O_3	22.05
Fe_2O_3	0.59
FeO	29.43
MgO	6.49
CaO	1.80
H_2O+	0.13
H_2O-	.06
TiO_2	.07
P_2O_5	.05
MnO	1.57
Total	100.27

the analyzed specimen from the gneiss northwest of Edwards (Table 5). Presumably all the garnets in the gneiss of this region have about the same composition. Most of these garnets are a deep pinkish red to wine red. They occur as rounded, highly embayed forms, 1/16 to ½ inch in diameter. Quartz, biotite, a late chlorite, and potash feldspars are common inclusions. Frequently the garnets are enveloped in, or occur along, a cluster of quartz grains. The quartz is in turn enclosed in quartz and potash feldspar, or bordered on one side by gneiss and on the other by quartz-potash feldspar injection material.

The general concept that the garnets have developed in conjunction with invasion of the gneiss by granitic fluids, and their reaction with the gneiss, especially with the biotite therein, is in no way antithetic to the idea that some iron in excess of that already in the gneiss was added locally to the same rock at the inception of granitic emplacement. Certainly the averages of the majority of specimens of slightly garnetiferous gneiss tend to be no higher in iron than the unaltered country rock, and many are much lower. This trend is apparent in most examples where garnet is found in specimens only slightly granitized (Qb28 and Qb38, Table 2). In these specimens which average 3 and 4 per cent garnet, respectively, the gneiss shows a rudely equivalent decrease in biotite content. The same trends are shown by the least-granitized specimens of garnet-bearing gneiss in Figure 10, and far more conclusively by the average compositions of garnet-bearing

gneiss (Table 6). These data indicate the general evolution of garnet at the expense largely of biotite at that point.

These represent the general trends, as do the data of Figures 5, 6, and 7 and Table 4, which show the diminution of iron from the inception as field relations, suggests that this potash feldspar is not introduced, but reflects instead a progressive step in metamorphic reconstitution of the sediment.

The Edwards area is not only much closer to the large igneous granites of the Adirondack

TABLE 6.—AVERAGE MINERALOGICAL COMPOSITION OF QUARTZ-BIOTITE GNEISS MAPPED IN AREAS NEAR HYATT, EDWARDS, AND BALMAT, NEW YORK

Area	Hyatt sector	South Edwards	South Balmat
Number of specimens	58	36	16
Quartz	38	34	33
Plagioclase	32 (An^{29-35})	37 (An^{38})	35 (An^{35})
Potash feldspar	13	15	18
Biotite	15	9	11
Garnet	0.5	3	2
Pyrite	1	0.25	0.5
Other accessories	zircon magnetite muscovite sphene, hornblende tourmaline apatite calcite sillimanite chlorite	zircon magnetite epidote sphene calcite hornblende sillimanite chlorite	zircon magnetite sphene calcite sillimanite chlorite

of obvious injection and granitization in the gneiss of the Hyatt sector. But, as in the garnet-free segments of gneiss, there are very local relicts which indicate that some early garnet, like some biotite, has formed in conjunction with an early influx of iron-rich emanations.

These relations and others of interest appear as the gneiss is traced from the Hyatt sector northeast to the area north of Edwards—hereafter the north Edwards area. There garnet and sillimanite are abundant (Fig. 4) although not quite so closely associated with pegmatitic and granitic injection material. Some garnet occurs in relatively uninjected and unaltered segments of gneiss north of Edwards and is readily inferred to reflect the straightforward reconstitution of the gneiss under conditions of elevated temperature. Moreover, examples of plagioclase as calcic as sodic labradorite appear very locally in the gneiss. Small quantities of potash feldspar—up to about 5 per cent—also appear in parts of the gneiss seemingly at the expense of sericite. The bulk composition of the rock as calculated from the mode, as well

massif, but also is not far removed from syenitic intrusives (Fig. 1; *see also* Buddington, 1948, Pls. 1–3). It was undoubtedly a site of higher temperatures during metamorphism and more truly igneous granite than the Hyatt sector. In addition the rocks of the north Edwards area are, like those in other areas along the boundary of the igneous massif, more widely and thoroughly sheared out during metamorphism. Cataclastic and cataclastic-granoblastic textures are common. Where the rocks are not badly crushed the textures may verge more toward crystalloblastic types than those of the Hyatt sector. Relict layers with little or no injection material are far less abundant than in the Hyatt sector, although those which have been preserved indicate the same constancy and peculiarities in the composition of the metasediment.

In the north Edwards area, the greenish-brown biotite is rare. The garnets tend to have a slightly lavender cast. The analysis in Table 5, which represents $alm_{65.9}$ $pyr_{25.8}$ $spess_{3.5}$ $gross_{3.2}$ $andr_{1.9}$ (index 1.799) seems to be a

typical specimen. Other garnets in this area have indices of refraction ranging from 1.795 to 1.804 and averaging about 1.80. Garnet has been formed more widely than sillimanite in this region presumably at somewhat lower temperatures. In addition some garnet, reddish biotite, and possibly potash feldspar may have formed in little-injected gneiss in response to temperatures higher than those in the Hyatt area to the west. The distribution of garnet is consistent with the data from the Hyatt sector where garnet is also more widely distributed than sillimanite and, in addition, occurs in a few places with the greenish-brown biotite, which is exceptionally rare with sillimanite. As the Edwards area is approached from the southwest, garnetiferous gneiss becomes the dominant facies (Fig. 4). Sillimanite is at first patchy in its distribution, becoming more ubiquitous north of Edwards (Pl. 2). In this area and even more clearly in the vicinity of the California phacolith just southwest of Balmat (Figs. 1, 4) sillimanite has formed synchronously with the garnet, and at least locally after garnet was being resorbed by later granitic fluids. The relations suggest that, although most of the sillimanite of these areas has evolved with garnet, some, especially along shear zones, has formed through the differentiation of relatively localized aluminous layers in the gneiss and migmatite (Pl. 2). Most of the shear zones in question are rooted in the alaskitic granite of the California phacolith, the probable source of the fluids which may be inferred to have facilitated the differentiation. These zones are also sites of pronounced retrograde metamorphism along which reddish biotite is altered first to still another distinctive type of greenish biotite and then to a chlorite. The associated sillimanite and feldspars are sericitized, silicified, and, uncommonly, replaced by serpentine.

Characteristic examples of garnet with reddish-brown biotite and, locally, sillimanite appear in most segments of the gneiss where it borders the igneous massif. In this category is the large elliptical mass south of Edwards, the south Edwards gneiss—which Brown (1936) concluded was a separate, older formation. Apart from the field relations, which the writers think oppose Brown's thesis, the texture and composition of this gneiss accords perfectly with garnetiferous types of the main belt. Most of the south Edwards gneiss is a typical migmatite merging locally into granite. Both marble and amphibolitic interlayers appear in associations with gneiss like those in the main gneissic belt. The central part of the mass is more granitic than its outer parts, and Buddington (1929, p. 74–75, Fig. 33) originally described the body as a phacolith. Later Buddington (1948, p. 37) pointed out possible relations between features of the south Edwards granitic injection material and sillimanitic, garnetiferous microcline granites (alaskites) of the igneous massif.

The significant relations are clearly those of a highly sheared and folded segment of garnetiferous gneiss, injected and granitized, probably by magma of alaskitic composition as well as emanations from magma, in proximity to the igneous massif. In respect to the affinities of the south Edwards gneiss and the evolution of its mineral facies, it is instructive to compare it with a segment of the major gneiss belt south of Balmat (Fig. 1). There the major belt curves southward, and its southern and probably uppermost layers envelop the California phacolith, also alaskitic granite. To be sure, the gneiss in the south Balmat area is a little farther from the igneous massif than that south of Edwards, and it is not so highly deformed or pervasively modified by granitic emanations. The south Balmat facies of gneiss is clearly part of the main gneiss belt, however, and in it are developed textures and facies which completely overlap the types found in the Hyatt sector on one hand and the south Edwards gneiss on the other. Mineral compositions believed to represent these three segments of gneiss (Table 6) have been obtained by averaging modes of large numbers of widely distributed, and "typical" gneissic layers. Although the averages of both the south Edwards and south Balmat areas include garnet and sillimanite, much of the gneiss in these segments contains no sillimanite, and locally garnet is absent south of Balmat. The cordierite listed as an accessory in the south Edwards average is from several small closely spaced areas.

The biotite of the south Edwards gneiss is the reddish-brown variety, which locally has

a γ index as high as 1.654. Most of the biotite south of Balmat is the reddish variety also but with, on the average, a lower index. Locally greenish biotite appears, but, as in the gneiss of the Hyatt sector, the examples of greenish-brown biotite south of Balmat are confined largely to the least-injected, garnet- and sillimanite-free layers.

TABLE 7.—MINERALOGICAL COMPOSITION OF INCIPIENT TO APPRECIABLY GRANITIZED GNEISS THAT IS ALSO ABNORMALLY BIOTITIC

Specimen number	Qb16	Qb32	Qb14	Qb26	QbC	Qb29
Quartz	41	30	36	27	21	31
Oligoclase or oligo-andesine	25	20	34	10	25	30
Biotite	20	20	20	21	23	24
Potash feldspar	9	14	10	37	31	12
Garnet	3	3		R		3
Sillimanite	1	13		5		R
Magnetite	tr.	tr.	tr.	tr.	tr.	tr.

Noteworthy features of the averages of the gneiss both south of Balmat and south of Edwards are (1) their similarity, (2) their decreased biotite content (as compared with gneiss of the Hyatt sector), and (3) the abundance of potash feldspar, chiefly microcline. The compositional features of the south Edwards gneiss are certainly those which might be predicted in the major belt of gneiss wherever it interacted with and was modified by granites at the relatively higher temperatures along the border of the Adirondack massif.

The averages of modes of the garnetiferous and sillimanitic gneiss in Table 6 exhibit little or no evidence of the early-stage mafic inoculation of the gneiss which has been inferred from scattered, biotite-rich layers in the Hyatt and north Edwards sector. Biotite-rich layers suggestive of the addition of iron and magnesia to gneiss in the early stages of its injection appear locally in all these areas, however, in close association with pegmatitic and granitic material. Some of these mafic types are plotted in Table 7 along with the earlier-noted mafic type Qbc from the Hyatt sector. Specimens of this type are clearly anomalous in their combined high-biotite, high-potash feldspar and garnet content. Moreover, those which are garnetiferous do not show the more typical diminution in biotite. All exhibit comparable field relations—they are of infrequent occurrence, postdating the relict, least-altered gneiss and partly obliterated by succeeding stages of granitization in which mafic components tend to be expelled.

Interaction of Gneiss and Granites in the Central Adirondack Massif

The typical "Hermon type" inequigranular granite complex which has been described in the preceding pages as the widespread hybrid rock evolved by interaction of granitic components and gneisses of the lowlands is an unimportant type in the igneous massif. Buddington (in preparation) has described several occurrences in the Oswegatchie and Russell quadrangles where the augen of microcline are typically developed but the quartz content is reduced to 15 or 20 per cent and biotite ranges from several to 7 per cent.

Important facies of two of the four major igneous granites of the massif are described by Buddington (in preparation), however, as products of contamination of granite magma by the gneiss. In these contaminated facies of both granites, garnet, sillimanite, and biotite are conspicuous as products of the interaction. The following data on these rocks and minerals are taken from Buddington's unpublished report.

One of these granites within the massif which has shredded and engulfed the gneiss is of the alaskitic volatile-rich type also manifest in the Lowlands as the typical phacolithic granite. In and along the margins of the massif Buddington notes that this alaskite has intruded and shredded the gneiss and a slightly biotitic, sillimanitic, and garnetiferous facies has developed. This granitic fluid is inferred to be part of that which has injected the south Edwards sector of gneiss, as well as that enveloped by gneiss southeast of Balmat (Fig. 1).

The second granitic type of the massif which includes gneissic contaminates is interpreted by Buddington to be largely of replacement origin. It is a fine-grained granite in which the feldspar is preponderantly microcline. Thin

TABLE 8.—CHEMICAL COMPOSITIONS AND MODES OF SOME GRANITES FORMED BY INTERACTION OF MAGMA AND QUARTZ-BIOTITE-OLIGOCLASE GNEISS

Specimen number	Qb-11	PG-18	EG-28	B12-A	B12-B	B13
SiO_2	64.18	72.35	69.40	71.34	70.99	71.44
Al_2O_3	16.19	12.94	15.63	13.64	14.28	14.89
Fe_2O_3	1.87	1.13	0.60	.77	1.19	2.40
FeO	3.98	1.52	0.62	3.97	2.30	1.38
MgO	2.17	0.72	0.14	.29	0.53	0.30
CaO	2.69	1.33	0.18	1.45	1.12	0.50
Na_2O	4.64	4.22	5.03	1.76	2.80	1.36
K_2O	3.48	4.90	7.73	5.26	5.97	5.99
H_2O+	0.24	0.18	0.18	0.27	0.30	0.52
H_2O-	0.06	0.05	0.04	0.05	0.08	.08
TiO_2	0.34	0.10	0.04	0.64	0.26	0.65
P_2O_5	—	—	—	0.08	0.2	0.22
MnO	0.06	0.03	tr.	0.05	.09	0.03
Total	99.90	99.51	99.58	99.57	99.93	
Modes						
Quartz	29	36	29		24.0	
Orthoclase				—		
Microcline	11	18	31		56.6	
Plagioclase	44	42	37		$10.1^{Ab_{90}}$	
Biotite	15	4	2		—	
Magnetite, fluorite, sphene, garnet, zircon, sillimanite, hornblende	1	1	1		7.8	

Qb-11 Porphyroblastic facies of Hermon type granite, from gneiss complex northwest of Hyatt. Analyst, Ledoux and Co.

PG-18 Porphyroblastic facies of Hermon type granite, north of Hyatt. Analyst, Ledoux and Co.

EG-28 Alaskitic granite in gneiss northeast of Hyatt. Analyst, Ledoux & Co.

B12-A Garnetiferous Hermon type granitic gneiss 1 mile west of Bear Pond, Tupper Lake Quadrangle. Analyst, Eileen H. Kane. (Quoted from A. F. Buddington, 1951).

B12-B Garnet alaskite contaminated with gneiss, Horseshoe Lake, Tupper Lake Quadrangle. Analyst, Lee C. Peck. (Quoted from A. F. Buddington, 1951).

B13 Sillimanite-quartz-microcline granitic gneiss, Skate Creek, Oswegatchie Quadrangle. Analyst, Lee C. Peck. (Quoted from A. F. Buddington, 1951).

sheets of this microcline granite with sillimanite, biotite, and garnet appear within the gneiss in the outer parts of the massif (Tupper Lake, Cranberry, Stark, and Russell quadrangles). These are distinguished by Buddington and Leonard from the alaskitic facies not only because their feldspar is preponderantly microcline, but also because they contain a higher percentage of iron oxides and apatite. Many of the sillimanite facies are rich in quartz. The sillimanite is in nodules, discs, and lenses, some as much as 6 inches long and an inch thick. Locally a muscovite facies of this hybrid granite is formed in which the biotite and some sillimanite are altered to that mineral.

In Table 8 are analyses quoted from Buddington's report of several of the above-mentioned types. The analysis of garnetiferous "Hermon" type (B12-A) by Eileen H. Kane is from the Tupper Lake quadrangle near Bear

Pond. The sillimanitic microcline granite (B-13) analyzed by Lee C. Peck occurs in the Skate Creek area, Oswegatchie quadrangle, and the analysis of garnetiferous alaskite (B12-B) by Peck is of a contaminated facies of the alaskitic granite near Horseshoe Lake, Tupper Lake quadrangle.

Comparisons of the compositions of these granites, all of which are contaminated by the gneiss, with analyses of the Hermon types from the Lowland, repeated from Table 4, show both parallels and contrasts. The silica content of both the granites of the Lowlands and those of the Massif, and of the gneiss as well, is essentially the same. The granites of the massif described by Buddington are, however, richer in iron—possibly derived largely from the gneiss formerly in the massif area—than all but the most gneisslike types of the Lowlands, and much of the magnesia and soda derived from the gneissic inclusions in the massif appears to have been sweated out of the system. Much of the magnesia also has been expelled during the evolution of the Lowlands "Hermon" types (PG-18 for example), but their Na_2O content is well in excess of that in either the remarkably sodic gneiss or of that inferred to be in the invading granitic fluids. The TiO_2 of the gneiss is also apparently lost during the evolution of the Lowlands granite, whereas the granites of the massif were either initially high in titania or have retained that originally incorporated in the gneiss. Buddington has suggested that much of the granitic fluids which have permeated and reacted with the gneiss of the lowlands to form the Hermon types originated as volatile-rich differentiates of certain of the granite magmas in the massif, and that some of the soda in those fluids was sweated out of the gneiss in the massif by these parent magmas.

Origin of the Gneiss

General Statement

The inferred pre-metamorphic features of the gneiss hardly point to an obvious type or origin for the parent sediment. The principal difficulties in the way of setting up an attractive hypothesis appear with the necessity of relating the postulated chemical composition of the sediment and its stratigraphic associations. The thick, persistent, uniformly layered marbles and clean quartzites that lie stratigraphically above and below the gneiss seem conformable with it. Moreover, several uniform carbonate zones occur as interlayers within the gneiss. These relations are best harmonized with the concept that the gneiss is derived from shales or argillaceous sandstones, themselves the product of moderate to intensive residual weathering and good sorting. The inferred composition of the gneiss however, especially the high Na_2O/K_2O ratio, seems incompatible with this concept. The nearest analogue to the gneiss in terms of composition are graywackes which must be derived with a minimum of chemical weathering, hastily transported and deposited, almost invariably with other sediments that reflect a highly unstable crustal environment. Some tuffs, especially grandioritic or dacitic types, also approach the gneiss in composition, but their occurrence as a thick, uniform, and laterally continuous zone in this segment of the Grenville series is as incongruous as that of graywackes.

An alternative is that the present composition of the least-altered gneiss has been induced either during sedimentation or by a secondary, possibly metamorphic process. If secondary changes are considered, two somewhat opposed origins may be postulated. The gneiss could be thought of as a veinitic migmatite whose high Na_2O/K_2O ratio is the result of preferential extraction of potash, conceivably to form the potassic, granitic ichor which now forms the migmatizing and granitizing substances in the gneiss. The alternative is that soda, or sodium ion, has been added to the sediment by some post-diagenic process. The remarkably high total of $Na_2O + K_2O$ might be interpreted as favoring such an origin for the gneiss. Both these alternatives, of abstraction of potash, or addition of soda, and any combination of the two appear inadequate however for reasons discussed below. More tenable origins of the gneiss are either that the parent sediment was derived from sodic terranes with a minimum of chemical alteration, or that soda was added to the sediment during or soon after deposition. With the first-named possibility, graywacke-type sediments and tuffs remain the most

logical parent rocks. If, on the other hand, soda was added to the clastic particles at the interface of deposition or penecontemporaneously, the pre-existing sediment may have been one of the more common clay-weathering products. Sodic shales form at least locally from montmorillonites, especially through base exchange or by other processes of reconstitution. Some water-laid tuffs likewise alter to soda-rich zeolites and zeolitelike minerals during or soon after deposition in saline waters. Inasmuch as the Grenville seas appear to have been abnormally saline over protracted periods of sedimentation, the addition of sodium at the expense of another cation in the sediment becomes even more credible. No hypothesis seems attractive enough, however, to warrant its enthusiastic endorsement. Each appears to have certain attractive aspects as well as defects which are enumerated below as a basis for subsequent investigations.

Possible Processes of Veinitic Migmatization

All the concepts of origin of the gneiss heretofore published—and the foregoing discussion as well—have been based on the premise that the complex is an arteritic migmatite; that is, the gneiss is interpreted as having been injected, permeated, and replaced by granitic components originating outside the Grenville series. An agnostic might conclude that this interpretation is a product of indoctrination and that about the same lithologic interrelations could result from either arteritic or veinitic migmatization. Two critical features of the gneiss—its high ratio of Na_2O to K_2O, and the relatively large amount of intimately interlayered potassic pegmatite veins—suggest that K_2O could have been leached from the metasediment.

If a potash-rich granitic ichor were derived from the sediment itself, however, the many "oldest" quartz-biotite-oligoclase layers ("least-altered gneiss") which are so widespread and uniform in composition become intermediate type facies, that is, residues of more felsic antecedents. This assumption has been discarded as untenable. It implies that widely separated parts of the gneiss were all selectively leached or fused to this constant composition, no matter what their distribution in terms of intensity of metamorphism or structural form. An especially important factor is that the area of occurrence of the quartz-biotite-oligoclase facies of the gneiss in the Northwest Adirondacks includes the Hyatt (Fig. 4) and other sectors of least deformation and lowest-rank metamorphic facies. Consequently, in the broad, arcuately zonal pattern of the Adirondack metamorphism, large-scale and uniform metamorphic differentiation or selective leaching of metasediment would have to be postulated, not only for areas of differing intensity of metamorphism, but also for one of the lowest temperature-pressure environments in the region[3] and for a sector in which shearing and refoliation was at a minimum.

Data from other parts of the Adirondacks furnish additional arguments against the derivation of the felsic ichor from the gneiss itself. Layers of quartz-biotite-oligoclase gneiss form a major part of the Grenville series in both the southern and eastern Adirondacks. In parts of the Paradox Lake quadrangle and in the New York part of the Ticonderoga quadrangle (Eastern Adirondacks), for example, Matt Walton (oral communication) very tentatively has assigned a thickness of 1500 to 2000 feet to a monotonous unit of about this composition. Although a positive correlation of this quartz-biotite-oligoclase gneiss and that in the Northwest Adirondacks is clearly unwarranted, available data, especially the stratigraphic relations, certainly favor the inference that these segments are parts of a single formation.

The relict gneissic layers in the Grenville series of the Piseco Lake quadrangle of the southern Adirondacks (Cannon, 1937, p. 41–44) also seem to have many lithologic features and a composition approaching the quartz-biotite-oligoclase gneiss of the region between, say, Antwerp and Russell.

Migmatitic types abound in these three widely separated areas, but all the more potash-rich types known appear to intrude and postdate both gneiss and other associated rocks of the Grenville series.

[3] This would be designated the amphibolite facies, staurolite-kyanite subfacies in Turner's classification (1948, p. 81–85).

Another factor opposing the concept of a veinitic migmatite is the composition of those granites and veined gneisses in the Northwest Adirondacks which might be considered exudations from a parent gneiss. The granitic and pegmatitic types contain about the same volume of total silica as any inferred residual layers (*compare* EG28 or PG18 with QbA or Qb2, Table 4) and in addition a higher alumina content. Via the differential anatexis of Eskola (1933, p. 24), the residua should not only be more mafic but also higher in "the excesses"—that is, total silica and alumina—than the exudate.

Volume considerations also suggest that the granitic components are introduced into the gneiss. Granitic components bearing what seem to be consistently the same paragenetic relations to the metasediments and with about the same compositional and textural peculiarities have injected and permeated the entire Grenville series of the Lowlands areas, and all earlier mafic intrusives as well. Especially pertinent examples are the many lenses and irregular masses of pegmatite and granite along the margins of the gneiss, partly interfingering with it and partly projecting into associated marble, quartzites, and amphibolites.

TABLE 9.—APPROXIMATE MINERALOGICAL COMPOSITION OF SOME GNEISSIC INTERLAYERS IN MARBLES OF THE GRENVILLE SERIES

Mineral	Reference number					
	1	2	3	4	5	6
Quartz	52	20	36	41	19	40
Potash feldspar	38	38	41	19	37	1
Oligoclase	0.5	14	1	5	5	39
Biotite	1	19	—	7	33	17
Muscovite	4	3	9	5		0.4
Pyrite	3	0.5	9	5	0.5	0.1
Sillimanite		tr.	.5	1	2	
Accessories	1.5	4.5	3.5	17	3.5	2.5

1. Average of 15 modal analyses of least injected layers of granulite facies in feldspathic gneiss interlayer, Balmat-Edwards marble belt.
2. Average of 12 modal analyses of least injected layers of biotitic facies, in feldspathic gneiss interlayer, Balmat-Edwards marble belt.
3. Average of 8 modal analyses of least altered layers of feldspathic facies in pyritic schist interlayer, Balmat-Edwards marble belt.
4. Average of 6 modal analyses of least altered layers of biotitic facies in pyritic schist interlayer, Balmat-Edwards marble belt.
5. Average of 5 modal anlyses of least altered layers of gneiss interlayer in Gouverneur marble belt.
6. Average of 15 least altered layers of quartz-biotite-oligoclase gneiss listed in Table 2.

The volume of this felsic material within the Northwest Adirondacks region is considerably larger than that of either the gneiss proper or of any parent to gneiss which may be inferred on either stratigraphic or structural grounds. The alkalic, potash-rich offspring would have emerged much larger than the parent. Moreover, in whelping this giant, the parent gneiss would be required, without disturbing its make-up, to maintain many obvious stratigraphic relations and sedimentary features. Surely such pervasive and widespread differential anatexis or other process of veinitic evolution would have materially blurred or obliterated the sedimentary relicts at the very places where they now appear to be clearest.

Possible Inoculation of Soda after Diagenesis

Consideration of the possibility of a veinitic differentiate provokes but seems to answer the question of whether the concentrations and ratios of Na_2O and K_2O in the quartz-biotite-oligoclase layers are the product of post-diagenetic inoculations of, for example, Na_2O into the gneiss. If the critical concentrations of the alkalis in the assumed least-altered layers were the product of additions and losses induced by metasomatizing fluids from outside the gneiss, after the sediment was deposited, these changes, like the losses of potash contemplated above, must have been so uniform and pervasive as to leave no trace of the process, especially no unenriched relicts. Moreover, if the foregoing alterations are assumed in the northwest Adirondacks, they must be adapted to segments of similar and probably correlative gneiss throughout the southern and eastern Adirondacks. Uniform and pervasive secondary changes of this kind, on this much larger scale, would seem still less probable. They are conceivable to us only if they occurred at the interface of sedimentation or as related diagenetic

processes. Possible alterations at this earlier stage are discussed on a later page.

Additional data oppose the secondary inoculation concept and set important limits upon our speculations of the origin of the gneiss. Both marble zones that enclose the gneiss in the Northwest Adirondacks contain important interlayers of clastic sediment, in which soda is not present in excess of K_2O. Some averages of modes of probably least-altered layers are assembled in Table 9, alongside an average of the least-altered layers of quartz-biotite-oligoclase gneiss. Very probably some of the potash in the gneissic interlayers in marble has been introduced, for these units are relatively thin and highly injected. Nevertheless the compositions of these interlayers in the marbles all are more nearly consistent with mixtures of Clarke's average shale (Table 11) combined with various amounts of a typical sand. Even if half the potash feldspar in most of these layers is introduced, and a fourth of the soda removed (which is highly improbable), the resulting ratio of Na_2O to K_2O does not exceed 0.75.

Both the pyritic schist and feldspathic gneiss, whose least-altered layers are averaged as examples 1 to 4 inclusive, Table 9, occur within the marble zone southeast of (above) the gneiss. The pyritic schist is within 150 feet stratigraphically of the quartz-biotite-oligoclase gneiss. The feldspathic gneiss (Brown's median gneiss, 1936, p. 238) lies near the center of the same marble belt, stratigraphically 1200 feet higher in the section. The gneiss from the marble northwest of (below) the quartz-biotite-oligoclase gneiss is within 250 feet stratigraphically of the basal layers of the more sodic major gneiss. Moreover both pyritic schist and the thin gneiss interlayers in the marbles have been forced into contact with the margins of the major gneissic unit during deformation. Any significant chemical alterations of one facies during deformation should be reflected in the others.

Additional examples of typical shales and sandy facies now more or less injected and granitized appear as interlayers in the marbles at positions more widely separated from the quartz-biotite-oligoclase gneiss. If any widespread, post-depositional additions of soda have occurred in the Grenville series, the question arises why these additions are confined to the major gneiss, and distributed so uniformly and pervasively through it.

Possible Sedimentary Origin

The above considerations have led us to conclude that either (1) the quartz-biotite-oligoclase layers had essentially this composition at deposition, or (2) modifications, such as an increase in soda and possibly a concomitant loss in K_2O, were induced as the sediment was deposited or as a diagenetic process through the interaction of sediment and sea waters.

In effect the first alternative seems to require a clastic sediment such as certain graywackes or tuffs in which the requisite concentration of soda, especially, has never been freed into solution by chemical weathering of the source-rock particles. Such sediments are derived largely by physical processes with minor or only moderate leaching unless very special weathering products are postulated. Appreciable chemical weathering of most igneous or metamorphic rocks would free the soda for removal in solution and reduce the Na_2O to K_2O ratio below 1. The finer the particle size of the sediment, the greater the impoverishment in soda. (*See, for example,* Pettijohn, 1949, p. 273, and Table 82, p. 283; Grout, 1925; and Goldich, 1938).

The typical shales associated with carbonate-rich sediments and clean quartzites all have a Na_2O:K_2O ratio of about 0.4 (*see also* Conway, 1945; and Nanz, 1953), and in many modern shales the Na_2O:K_2O ratio is as low as 0.33 (Grim, Dietz, and Bradley, 1949, Table 4, and p. 1799); whereas the data from the gneiss are all consistent, and, after repeated re-examination, compelling in indicating a Na_2O:K_2O ratio of 1.29 with Na_2O content at about 3.75 and K_2O at 2.90. There are, of course, other differences between the composition of either individual or average shales and the specimens of least-altered gneiss (QbA, Qb2, and 4537, Table 3; QbA, Table 12), but these differences tend to disappear if one part average sandstone is mixed with two parts average shale (column 1, Table 11). This sort of mix, when compared with analysis QbA, leaves only K_2O, Na_2O, CaO, and the oxidation states of iron out of line. The differences in

lime certainly are not critical, and the differences in the states of oxidation of iron readily could be brought into convergence by metamorphism. The variations in Na_2O and K_2O between QbA and the sandy shale are critical, however, and cannot be eliminated by any mix of clastic sediments derived through moderate or thorough weathering. The differences in composition of typical graywackes, as well as the gneiss, from Clarke's average shale also are reflected in the triangular ACF projection (Fig. 11).

TABLE 10.—GRAIN-SIZE DATA ON QUARTZ, PLAGIOCLASE, AND BIOTITE*
(In mm.)

Mineral	Specimen number	Approximate width: First quartile	Median	Third quartile	No. grains examined	Approximate length: First quartile	Median	Third quartile	No. grains examined	Corrected average median†	Ratio L. W.
Quartz	Qb 12	.074	.127	.160	88	.083	.171	.242	52	.196	1.3:1
	Qb 72	.072	.111	.167	48	.125	.266	.401	38	.247	2.4:1
	Qb 58	.034	.089	.122	54	.044	.078	.142	54	.109	1:1
	Qb 3	.053	.106	.137	36	.129	.209	.281	32	.207	2:1
Plagioclase	Qb 12	.103	.183	.368	60	.100	.263	.426	54	.293	1.4:1
	Qb 72	.092	.178	.243	46	.174	.243	.385	24	.276	1.4:1
	Qb 58	.070	.130	.226	32	.110	.213	.396	40	.225	1.6:1
	Qb 3	.082	.215	.371	22	.121	.275	.379	20	.322	1.3:1
Biotite	Qb 12	.031	.051	.074	54	.132	.200	.278	52		4:1
	Qb 72	.033	.050	.075	48	.162	.213	.270	42		4.3:1
	Qb 58	.048	.070	.069	40	.093	.134	.178	32		2:1
	Qb 3	.022	.041	.072	32	.099	.133	.168	14		2.8:1

* Data obtained from random traverses on thin sections of least deformed layers of gneiss in the Hyatt sector.

† Corrected average median = Average of approximate width and length medians/0.76.

LITHOLOGY AND DEPOSITIONAL ENVIRONMENT OF THE PARENT OF THE GNEISS

General Requirements and Relationships

The sedimentary parent to the gneiss must have been a clastic composed of fragments no larger, and probably somewhat smaller, than medium sand (0.5 mm.), unless the present grain size in the gneiss reflects either no appreciable change or a decrease during metamorphism.

Thus, the grain-size data (Table 10) of quartz, biotite, and oligoclase from least-deformed, relict beds reflect a medium- to coarse-grained sandstone. The quartz grains from the least-disturbed relict beds (Qb12 and Qb58, Table 10) have a length to width ratio of about 1.35:1 and 1.6:1 respectively and very approximate median grain sizes of 0.2 and 0.17.[4] Maximum grain sizes rarely exceed 0.5 to 0.65 in diameter.

Probably many or most of the constituent grains, even in these least-deformed layers of gneiss, were enlarged appreciably during the penetrative reconstitution of the rock. A decrease in grain size seems reasonable only if the neomineralization has evolved as a colony-type phenomenon, with many grains of the metamorphic minerals growing at the expense of one or several parent clasts. No penetrative cataclasis of the layers or of the entire formation appears consistent with the existence of numerous stratigraphic relicts and well-preserved sedimentary contacts. Certainly a pervasive granulation of the gneiss would require profound deformation throughout and is incompatible

[4] The rocks chosen show no lineations defined by grain shapes. The rough values noted were arrived at by averaging length and width data from random traverses (Table 10) and assuming these values were essentially 0.76 times the real ones (Krumbein, 1935).

with the patchy persistence of relict beds and stratigraphic relations (Fig. 3).

The uniformity of composition and texture throughout the least-altered segments of gneiss has been emphasized earlier. There are, of course, the several interlayers of marble and the numerous scattered, thin sheets of amphibolite. These particular amphibolite interlayers in the gneiss remain of obscure origin and may be evolved from calcareous sediments, from tuffaceous beds, or much less reasonably from mafic sills. Whatever the initial composition of the amphibolitic interlayers, those which are least deformed are sharply defined within the enclosing sediment now evolved into gneiss. Neither existing marble nor amphibolite layers are considered metamorphic differentiates for many of the same reasons the granitic interlayers are not. The marble especially is confined to several widely separated zones within the gneiss. A hypothesis of differentiation to account for the carbonate layers would imply profound remobilization of the gneiss.

Except for the amphibolite and marble, which compose no more than 15 per cent of the gneiss complex, there are very few constituent layers which might reasonably be interpreted either as more siliceous (sandy or cherty) interlayers, or of types transitional between, say, shale and a sandstone, limestone, or chert.

Another relationship, already emphasized as seemingly incontrovertible, is that the gneiss is intercalated in a sequence dominated by thick, relatively clean dolomitic marble quartzites and siliceous carbonate sediments.

Several features of these marbles are of particular interest and pertinence in suggesting the probable environment of sedimentation. One feature is the great thickness of these carbonate deposits which total at least 11,000 feet (before metamorphism) in the Northwest Adirondacks (Table 1). The two major marble belts which enclose the gneiss were each at least 5000 feet thick before metamorphism. Another very striking feature highly suggestive of the sedimentary environment is the occurrence of the anhydrite interlayers[5] as well as halite and natural gas in the marble above the gneiss. The known anhydrite beds are stratigraphically 1000 to 1500 feet above the gneiss and separated from it by interlayers of clean dolomite, a "stinkstone" or bituminous dolomite, siliceous (cherty?) dolomite, and the pyritic schist heretofore mentioned. Although the anhydrite almost never appears in surface outcrops, it could form a relatively common but as yet undetected interlayer in the marbles within and below the gneiss where no subsurface drilling and mining operations have been undertaken.

Still another important relationship is that the mappable units in the Grenville series—the component interlayers within the marbles, and the major units of marble and quartz-biotite-oligoclase gneiss as well—are essentially conformable where the relations have been studied and are least blurred by deformation. Marked unconformities well may exist in the section, but they cannot be persistent; rather they would have to merge along the strike into areas of essential conformity.

Depositional Environment

Seemingly important regional aspects of the Grenville series are worth consideration in conjunction with the above-stated sedimentary associations and requirements of a parent to the gneiss. These have been discussed in Part I and merely are summarized here. The great thickness of the Grenville series in the Northwest Adirondacks (probably 20,000+ feet before metamorphism) persists northwest into Canada, probably at least to Bancroft, Ontario. The marble units, and possibly to a lesser extent the gneisses, appear to thin eastward, however, in both the Adirondacks and in Canada (Pt. I, Fig. 1). At any rate a zone and probably a basin of deposition at least 200 miles long from northwest to southeast and 100 miles wide (and possibly much larger) is inferred for the marble-rich segment of the series.

The Grenville series in the Bancroft-Adirondack region is characterized by a "geosyncli-

[5] *See especially* Part I of these studies and J. S. Brown (1938). The occurrence and relations of these anhydrite interlayers are known almost solely through the excellent and detailed studies of J. S. Brown and N. H. Donald, Jr., of St. Joseph Lead Co., of marble in drill cores in the Balmat-Edwards District, N. Y.

nal-type" deformation, although lithologically it is not typical of the so-called geosynclinal environments. Conglomerates, pillow lavas, and other rocks of geosynclinal types, however, are inferred to occur just above, below, and possibly within the Grenville series in the western part of this area between Kingston and Bancroft, Ontario, and thence westward into the Madoc area. Immediately northwest is the so-called Grenville front, a pronounced discontinuity between, or change in, metasediments (Pt. I, Fig. 1; Tectonic Map of Canada, 1950) where the Grenville is juxtaposed to the Canadian Timiskaming series. Timiskaming rocks northwest of the Grenville front are strictly typical of geosynclinal environments and include graywackes, pillow lavas, and siliceous iron formations. (*See for example*, M. E. Wilson, 1939, p. 245–269.)

The above considerations seem to fit best the concept that the Grenville series, at least in the southwestern (Adirondack-Bancroft) part of the subprovince, was deposited on either a largely negative part of the earth's crust less stable than the floors of shelf seas (a marginal or intracratonic basin) or in the less active and marginal shelf segment of a major geosyncline (miogeosynclinal zone). The sedimentary facies of the presently defined miogeosynclinal associations may suggest both the eugeosyncline and shelf (Krumbein and Sloss, 1951, p. 364–392; Kay, 1951, p. 10) as is possibly the Grenville series in western areas above noted. Krumbein and Sloss (p. 368–369) have remarked in connection with the miogeosynclinal associations that:

> "Limestone may be abundant in some phases of miogeosynclinal sedimentation. Near the cratonic border, normal marine fossiliferous-fragmental and foraminiferal limestone may accumulate or be swept in from the shelf. Such limestones may aggregate several times the thickness of equivalent shelf deposits. The Mission Canyon and Rundle limestone (Mississippian) at the edge of the Cordilleran Geosyncline in Montana are of this type."

> "Farther in the miogeosynclinal belt, the limestone is dominantly normal marine or other dense to finely crystalline types. The Knox dolomite (Cambro-Ordovician) of the Appalachian Geosyncline border is an example."

Pettijohn (1949, p. 451–456) has noted the characteristic occurrence of orthoquartzite and shale in "foreland facies" which, as defined and illustrated by him, include both the miogeosynclinal and cratonal associations of Krumbein and Sloss.

An important additional requirement induced especially by the anhydrite interlayers is that, for a major period at least, sedimentation seems to have occurred in a restricted, highly saline sea. The maximum stratigraphic span of anhydrite layers is unknown, but a prolonged epoch of aridity and at least periodically enclosed seas is entirely consistent with and probably implied by the high magnesia and bitumen content of the marbles, the sporadic occurrence of halite, the abundant silica interlayers whose antecedents were probably chert, and indeed by the pyrite and graphite in many interlayers, although none of these features are unequivocally of sedimentary origin.

Facies of these types, found in intracratonic basins or miogeosynclinal zones, commonly are removed, however, from associations dominated by or characteristic of the thick tuffs and graywackes that offer a far easier compositional "fit" with the gneiss than do shales and siltstones more expectable in the cratonal and miogeosynclinal association. Graywackes and thick tuffs are confined almost exclusively to crustal troughs of greater instability (the eugeosyncline of Kay, 1951, p. 85–86). If either tuff or graywacke is therefore the inferred parent to the gneiss, the apparent conflict of sedimentary associations must be reconciled. Certainly neither graywacke of the requisite composition nor tuff in sufficient volume are to be expected within a siliceous, carbonate-rich sequence relatively low in iron.

Possible Sedimentary Antecedents

Graywacke.—Reference has been made to the striking similarities of the analyses of least-altered gneiss QbA, Qb2, or 4537 (Table 3) to many typical graywackes. This fit is apparent from inspection of Table 11 where the analyses III, IV, and V tabulated alongside QbA represent averages of analyses of Franciscan, New Zealand, and miscellaneous graywackes respectively. As noted in Part I, an excess of Na_2O over K_2O (Na_2O:K_2O::1.25 to 2.5) seems to be characteristic of certain graywackes found particularly in the eugeo-

synclinal association and is certainly the most significant difference in the chemical compositions of these rocks as contrasted with shales, silts, or sandy sediments derived as residual weathering products.

The same very striking parallel in bulk chemistry between certain graywackes and the gneiss is implicit in the metamorphic derivatives of graywacke. At intermediate to higher-rank metamorphism (amphibolite facies) the known graywacke sequences like the Missi Series (Ambrose, 1936) or the Otago schists (Turner, 1933) are reconstituted to assemblages of quartz, biotite, oligoclase, and garnet like those in the gneiss. The parallels between the inferred pre-metamorphic features of the gneiss and graywackes persist to most other lithologic features. Pettijohn (1949, p. 243–255) notes the following as characteristic features of graywackes: Color gray to black; texturally the rock includes sand or coarser fragments of quartz, feldspars, and rock fragments set in a claylike paste which equals or exceeds the volume of the larger detrital grains. In little-metamorphosed graywackes the matrix is a microcrystalline aggregate of quartz, feldspar, chlorite, and sericite. Many graywackes are thick, massive to faintly foliated, and may be mistaken for igneous rocks. Graded bedding or rhythmic alternation of graywacke and slate are common features.

All these above lithologic features except the slaty interlayers and the coarsest clastic components are consistent with the inferred pre-metamorphic features of the gneiss.

The massive, monotonous form and the great thickness of many graywackes and their superficial similarity to an igneous rock fit the gneiss precisely. (*See especially* Buddington, 1934, p. 65–66.)

The graded bedding characteristic of many graywackes or features suggestive of it have not been observed in the gneiss. Graded bedding in the parent to the gneiss could have been obliterated, however, in the pervasive reconstitution of the rock. Nor does the gneiss show any evidence of shaly interlayers, but F. J. Turner (oral communication) states that many of the thick, Mesozoic graywackes of New Zealand are devoid of slaty interlayers and are monotonously uniform in composition.

TABLE 11.—AVERAGES OF CHEMICAL COMPOSITIONS OF SOME GRAYWACKE SANDSTONES, SHALES AND COMPOSITE SANDY SHALES, TABULATED WITH AVERAGE COMPOSITION OF LEAST-ALTERED QUARTZ-BIOTITE GNEISS LAYERS

	I	II	QbA	III	IV	V
SiO_2	65.5	58.10	70.90	69.69	65.95	64.2
TiO_2	0.5	0.65	0.32	9.40	0.55	0.5
Al_2O_3	12.00	15.40	12.17	13.53	13.52	14.1
Fe_2O_3	3.10	4.02	1.31	0.74	1.94	1.0
FeO	1.7	2.45	4.12	3.10	4.18	4.2
MnO			0.04	0.01		0.1
MgO	2.0	2.44	2.32	2.00	1.88	2.9
CaO	4.5	3.11	1.55	1.95	3.10	3.5
Na_2O	1.0	1.30	3.74	4.21	3.73	3.4
K_2O	2.6	3.24	2.87	1.71	2.01	2.0
H_2O+	2.9	5.00	0.21	2.08	3.13	2.1
H_2O-	—		0.05	0.26		0.1
P_2O_5	0.1	0.17		0.10		0.1
CO_2	3.4	2.63		0.23		1.6
SO_3	0.5	0.64				
Total	99.8	99.15	99.60	100.01		99.8

I. One part average sandstone plus two parts average shale (Pettijohn, 1949, p. 271).

II. Average shale (Clarke, 1924, p. 34).

QbA. Analysis of composite sample of 24 least altered layers of quartz-biotite-oligoclase gneiss (Ledoux and Co., analysts).

III. Average of 3 analyses, Franciscan graywacke (after Taliaferro, 1943, p. 136).

IV. Average of 2 analyses, graywacke at Marlborough, New Zealand (after J. Henderson, 1934–35, p. 15).

V. Average of 11 graywackes of widely separated age and locality (after Pettijohn, 1949, p. 250).

W. M. Cady (written communication) reports the same uniformity of composition and absence of slaty interlayers in certain graywackes of the Central Kuskokwin region, Alaska. A possible objection to graywacke as parent to gneiss is that the coarser-size fraction in many graywackes exceeds that in the gneiss, and recrystallization would result in an even more coarsely crystalline gneiss. A graywackelike parent is not precluded, however, for Eskola (1932) and Vogt (1927) have pointed out that many clastic sediments of the graywacke type

have as coarse fractions grains which do not exceed medium sand in size.

The relatively fine-grained graywacke-type sediments described by Eskola are from the Archean sequences of the Fennoscandian Shield. Vogt (1927) cites the Silurian succession of the Norland-Swedish Lappmarken where the metamorphic derivatives of a more westerly facies of Silurian sediments are very similar in composition and other features (except associations) to the gneiss in the Northwest Adirondacks. These rocks appear to grade eastward across the Caledonian range into more typical shales. Vogt concluded that the compositional changes could be correlated with the "degree of residual character" of the parent sediment. That is, the westerly facies was a rapidly derived, "poured-in" type of sediment of the graywacke type. He emphasizes the differences in weathering phenomena implicit in "normal shales" as contrasted with clastics relatively high in soda and low in potash. Vogt (p. 489–490) thus noted that:

> "Three oxides MgO, CaO and Na_2O, diminish gradually and regularly with increasing residual character. ... Three oxides, K_2O, SiO_2 and TiO_2 increase with increasing residual character. Most marked in this respect is the potash. ... The amount of iron remains constant over a remarkably large range of compositions. Applying these principles to the problem here considered it is found that the schists of the mountain range in their western facies represent a relatively little weathered clay sediment, while the schists of the eastern facies are much farther advanced towards the final residual stage."

In certain respects a sodic shale or silt derived as Vogt has suggested would seem less aberrant within the carbonate-rich Grenville series than a more typical graywacke with its disseminated coarser sand fraction. Considerations of the origin of the graywacke type, however, certainly suggest that a shale similarly derived is a rare rock. The graywacke type, whether coarse- or fine-grained, presumably derives its soda content from that already present in the minerals of the source rock. The Na_2O (unlike K_2O in shales) is not augmented in conjunction with the mineralogical or chemical changes induced by weathering, or during sedimentation.

Moreover, as Vogt notes, soda is commonly one of the earliest substances lost during weathering (*see also* Steidtman, 1908; Leith and Mead, 1915; Goldich, 1938), and it invariably precedes potash. Consequently a most unusual source rock or type of disintegration is required to permit a breakdown of the provenance into large volumes of clay or silt-size material without the loss of much of the soda into solution.

In this respect a typical graywacke, in which the soda content occurs in large part in plagioclases of sand size, requires less restricted conditions for formation. In any event, a source area of rocks with a minimum Na_2O:K_2O ratio of 1.3 is a prerequisite. Spilitic suites of low-rank albitic schists, common in the known Archean terranes immediately west and north of the Grenville subprovince, would be ideal source-rock types. In many of these rocks, appreciable soda may be lost in weathering before the ratio of Na_2O:K_2O falls below the requisite 1.29 of the gneiss. Low-rank metamorphic types also appear to have the advantage of containing much of the soda in albite, which occupies a position of intermediate stability in weathering (Goldich, 1938, p. 56). That is to say, if factors other than mineralogical composition are comparable, albite is probably more stable under the impact of weathering than the more calcic plagioclases, pyroxenes, and most amphiboles. Consequently an albitic schist might stand a better chance of producing a graywackelike clastic sediment than a diabase, granting equality of terrane, climate, and physical properties in the two rocks. In the light of the mineral stability series, another favorable source rock would seem to be glaucophane schists or kindred types.

The arid or semiarid climate which seems to be implicit in the occurrence of anhydrite interbeds in the Grenville series should facilitate physical weathering and retard many chemical processes. Marked aridity and a resulting barren provenance might permit a longer span of time between erosion and deposition of a graywacke type without excessive alteration of the composite fragments. Climatic factors may be secondary, however, to a special tectonic environment in the evolution of graywacke sediments. Fischer called graywackes a "poured-in" type of sediment (1933), and Pettijohn (1949, p. 253–254) commented:

"Graywacke . . . is indicative of a special tectonic environment. . . . Very rapid deposition is implied by the muddy matrix (indicating thereby lack of sorting), by the massive and nonstratified nature of the thicker beds; by the lack of cross-bedding and ripple marks (which are evidence of reworking and sorting and are possible only if the sedimentation is not too rapid); by the graded bedding of some phases . . .; and by the extraordinary thickness of the sedimentary deposits characterized by graywackes."

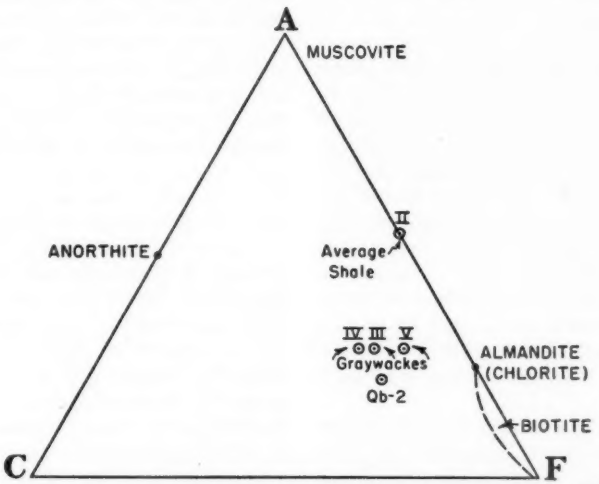

FIGURE 11. POSITIONS OF GRAYWACKES AND AVERAGE SHALE PLOTTED ON AN ACF DIAGRAM
The specimens III, IV, V, and Qb-2 are the same as those for which analyses are given in Table 11.

The requisite tectonism in the source area seems incompatible nevertheless with the evolution of the remarkably pure marbles and quartzose beds enclosing the gneiss. To derive the graywacke subaerially, these associations appear to require a single, sharply defined tectonic cycle in a near-by land mass, preceded and followed by periods when any such land areas are persistently near sea level and are contributing negligible clastic materials to the sedimentary site.

Conglomerates and pillow lavas, which appear to occur within the carbonate-rich Grenville series, imply equally rigorous and kindred demands. The occurrence of these contrasting sedimentary types would seem to minimize somewhat the importance that might be attached to the sedimentary associations of the Grenville gneiss. Graywackes, conglomerates, and pillow lavas dominate the eugeosynclinal zone just northwest of the Grenville front and could interfinger with Grenville deposits of peripheral areas.[6]

In this way the mixture of contrasting types might be explained as features of a zone of lateral transition. We know that equally aberrant although different facies associations are evolving on the floors of modern seas, possibly owing to the action of turbidity or density currents. (*See, for example*, Bramlette and Bradley, 1940, p. 14–16; Shepard, 1950, p. 35; Erickson *et al.*, 1951, p. 965.) Moreover, turbidity currents are believed to be exceedingly important as distributors of graywackelike sediments (Kuenen and Migliorini, 1950; Pettijohn, 1950). Pettijohn (1950, p. 70) has suggested that many graywackes are products of redeposition and have been eroded from other possibly well removed, submarine sites.

Although turbidity currents may well be important in sedimentation, there are few data to recommend them as a means of deriving the parent to the Grenville gneiss. It seems significant that, notwithstanding the possible

[6] This is neither to infer nor deny a correlation of the Grenville series with either the typically "geosynclinal" Timiskaming and other Archean sediments or the Huronian which border the Grenville series on the north and west.

association of conglomerates, volcanics, and marble of the Grenville series and of aberrant types in modern oceans, few if any examples of thick graywackes interlayered with thick, widespread carbonate zones have been recorded.

Unaltered tuff.—About the same or a greater degree of improbability exists in making the parent to the gneiss a tuffaceous sediment. A fair chemical fit is readily found as in the instance of graywackes. Tuffs approaching the composition of QbA, Qb2, and Qb4537 are reported. (*See for example*, Guppey *et al.*, 1931, p. 15; Hedin, 1940.) Moreover, both Gilluly (1936) and Buddington (oral communication) have noted that the compositions of certain dacites and quartz diorites (*see, for example*, Buddington and Chapin, 1929, p. 207–214) are not greatly different from that of the least-altered gneiss.

Neither intrusive igneous rocks nor demonstrable volcanics of the composition of quartz diorite and dacite appear in the Adirondacks, nor are any such well-defined igneous types characteristic of other parts of the Grenville subprovince. Moreover the known examples of "primary" tuff (as contrasted with redeposited alteration products) in other parts of the world, which are uniform in texture and composition throughout and fine-grained enough to compare with the ancestor to gneiss, are invariably thin, although of appreciable lateral extent. A corollary is that the described "tuffs" of rudely comparable composition which exceed 1000 feet in thickness and 500 square miles in lateral extent, and are not reworked, show a marked variation in size of constituents with included, coarser volcanic fragments, or lenses of igneous rock of roughly the same composition as the tuff itself. Most of the thicker and more extensive tuffs contain cherts, breccias, conglomerates, or other clastic facies. None are homogeneous and monotonous. Certainly none of the thicker tuffs (more than 1000 feet thick) reported in the literature are intercalated in a section dominated by very thick, clean dolomites, siliceous dolomites, and clean ("ortho") quartzites. (*See, for example*, Kay, 1951, p. 38–46, 49–57, 63–67.) The writers infer therefore that, if the parent to gneiss was dominantly of pyroclastic origin, this material would have to be reworked or redeposited, and presumably chemically altered at sites well removed from the foci of volcanism, to meet and harmonize the lithologic requirements and sedimentary associations.

Altered tuff.—Interestingly enough, however, a number of well-documented, thick, and widely distributed clayey types of sodic alteration products of pyroclastics are known. One dubious solution to the conflicts encountered in the consideration of unaltered tuffs and graywacke types as parents to gneiss seems to lie in certain of these.

There are, for example, zeolitic alteration products of pyroclastics such as the mineral clinoptilolite which Bramlette and Posjnak (1933) have found to be an important constituent of many clays derived from volcanic rocks. The clinoptilolite or a closely related zeolite-like mineral appears to be an intermediate product in the process of alteration of volcanic glasses, with bentonitic clay minerals as an end product. Comparisons of this sort of alteration with that which may have occurred in the sedimentary parent to gneiss are of particular interest for several reasons. Clinoptilolite with the composition as reported from Arizona bentonites (Table 12, with about 5 per cent admixed clay) would be chemically ideal as a major component of the pre-metamorphic Grenville sediment. Comparison of this analysis with QbA shows that the amounts and ratios of all major constituents, including alkalis, are very similar. Moreover, the occurrence of clinoptilolite as an alteration of volcanic material is neither localized nor confined to a primary rock of a single composition. Bramlette and Posjnak found the mineral in thick bentonites derived from a fairly calcic glass in the Pierre shale of the Black Hills area, as a common constituent of altered, less calcic, pyroclastics in the Miocene of California, and in bentonite from Arizona.

Still other zeolitic minerals have evolved as alteration products of pyroclastic materials in several instances as an "end product" of the interaction of ash and sea water. In two examples of special pertinence (Ross, 1928; Bradley, 1929), widespread beds of analcite and apophyllite have formed on lake and sea floors. Bradley (1929, p. 1) notes:

"The [analcite] beds are so unusual as to merit more than incidental record. They represent a new phase in the alteration of volcanic ash, and as an end product of that alteration they may perhaps be regarded as genetic relatives of bentonite, though their mineralogic composition and physical properties are utterly different. They indicate that analcite and apophyllite, which also occurs in these beds, can form at normal temperatures of the earths surface and without the agency of gaseous or liquid emanations from lavas or volcanic sources; ... because of their remarkable areal extent they serve as useful correlative units within the part of the Green River formation that contains the richest beds of oil."

In the instances cited above the alteration of volcanic materials to soda-rich minerals has occurred in sea or lake waters. Consequently, this process is a highly credible mechanism for adding soda to the sedimentary parent of gneiss during its deposition.

Both Bradley and Ross specifically note that the alteration is the result of interaction between the volcanic ash and saline waters of about the same type that may be inferred in the basin of Grenville sedimentation.

Bradley (1929, p. 6) concludes that the

"New minerals, stable under the new conditions, could in this manner form contemporaneously over very large areas—indeed, areas coincident with the extent of the lake at the time of each ash fall. Thus the analcite and apophyllite in the Green River formation appear to have formed as reaction products of the silica and alumina liberated by dissolving the volcanic ash with the solution of sodium, potassium and calcium salts that were either normal constituents of the lake water or that were also derived from alteration of ash."

Using these known types of alteration of pyroclastic as an analogy, a possible origin for the sediment now embodied in the gneiss may be visualized. Repeated and prolonged volcanic activity is manifest in the rocks of the adjacent Timiskaming and "Southern" subprovinces to the north and west of the region of the carbonate-rich Grenville series. We may infer that either volcanoes were active or volcanic rocks were being eroded and reworked during Grenville sedimentation. Source areas may have included submarine flows and falls of pyroclastics. Moreover, certain of these potential volcanic source rocks lie less than 500 miles from the Adirondacks and other parts of the evolving carbonate-rich Grenville series. It would seem, therefore, possible to assume that the clastic parent to the gneiss was a claylike sediment derived in large part or wholly from pyroclastic-rich sources, or, as an alternative, redeposited in the Grenville "basin" from extensive falls of land- or water-laid tuff.

TABLE 12.—CHEMICAL COMPOSITION IN WEIGHT PER CENT OF CLINOPTILOLITE FROM DOME, ARIZONA, ANALCIME FROM THE POPO AGIE MEMBER OF THE CHUGWATER FORMATION, AND COMPOSITE SAMPLE OF 24 LEAST-ALTERED LAYERS OF QUARTZ-BIOTITE-OLIGOCLASE GNEISS

	I	II	Qb-A
SiO_2	64.30	56.07	70.90
TiO_2		0.49	0.32
Al_2O_3	12.78	19.34	12.17
$FeO + Fe_2O_3$	0.82	3.58	5.43
CaO	2.42	0.64	1.55
Na_2O	3.96	8.24	3.74
K_2O	1.36	3.47	2.87
MgO	0.62	0.36	2.32
H_2O-	4.78		0.05
H_2O+	9.50	7.50	0.21
CO_2		0.18	

I. Clinoptilolite from Dome, Arizona with some 5 per cent admixed clay. F. G. Fairchild, analyst. (From Bramlette and Posjnak, 1933, p. 170).

II. Oolitic analcime from the Popo Agie member of the Chugwater formation, Maverick Springs, Wyoming. Bruce Williams Laboratory, analysts. (From Keller, 1952.)

Qb-A. Composite sample of 24 least altered layers of quartz-biotite-oligoclase gneiss. (Ledoux and Co., analysts.)

In introducing a fine clayey alteration derived largely or wholly from volcanics into the Grenville associations we would seemingly circumvent or reduce appreciably the problem of conflicting sedimentary associations. Moreover, a volcanic parent rock identical in composition with the least-altered layers of gneiss is not a prerequisite. In fact volcanic ash does not seem to be a necessary constituent in the evolution of zeolite-rich beds. Keller (1952) for example has described an impressive example of zeolitic, argillaceous sediments formed through the alteration of claystones presumably of nonvolcanic origin. He notes that analcime is prominent and characteristic in the Popo Ago "beds" which constitute a member of the Triassic Chugwater formation

of Wyoming. The analcime-containing beds are up to 60 feet thick and are laterally persistent over an area of at least 6000 square miles. The analcime is distributed throughout the Popo Agie member with silt and clay to form a massive to somewhat nodular "claystone" or "siltstone." No evidence of volcanic material was found. Keller (1952, p. 81) notes that "Careful search in the thin sections from the Popo Agie failed to locate any shards, feldspar, mica, or other fragments indicative of volcanic dust." Other components are relatively scanty, however, and the bulk of the unit is analcime. An analysis of the material (Table 12) shows an Na_2O content of 8.24 per cent and K_2O 3.47 per cent by weight.

The Chugwater formation, of which the Popo Agie is a member, is largely a thick sequence of reddish siltstones and sandstone with interlayers of gypsum and thin, flaggy dolomite. The siltstones are defined as subgraywackes by Krumbein and Sloss (1951, p. 363), and the entire sequence is designated an "unstable shelf deposit." Keller notes (1952, p. 70):

> "The analcime in the Popo Agie is believed to have originated from the interaction of hydrous aluminum silicate clay minerals with sodium rich waters of a large interior marsh lake. It probably represents an aluminum silicate mineral stable under the special saline environment, analogous to certain clay minerals which are stable under soil-forming or marine environments."

Clinoptilolite, analcime, and apophyllite offer a range of soda content from roughly 4 to almost 9 per cent with ratios of Na_2O to K_2O of about 3.0 to 7.5. In addition the amounts and proportions of the other elements are such that combinations of one or more of these minerals with certain commoner argillaceous sediments (Grim *et al.*, 1949) could result in a composition approximating that of QbA.

Sodic clays and shales.—A closely related alternative is that true clay minerals rich in soda may result from the interaction of chloride, alkaline, or sulfate types of "sea" water (Clarke, 1924, p. 176–180) on, say, montmorillonitic clays, especially at temperatures in excess of those which pertain in open seas. Thus, if Grenville sedimentation did take place in restricted seas and during prolonged or periodic aridity, both the abnormal soda content of the sea and the elevated temperatures might have induced either a preferential adsorption of Na_2O by clays, or their reconstitution into soda-rich types.

Periods may be envisaged when the sea waters were relatively impoverished in lime and possibly in magnesia, which has been precipitated with lime to form thick dolomites. Under these conditions, appreciable concentrations of soda might be fixed on or in clays at their deposition.[7]

Apropos of this possibility Kelly and Liebig (1934, p. 359) note that, where clays containing one exchangeable base are exposed to solutions rich in other exchangeable bases, the relative extent to which the bases in solution will take part in the reaction will be determined chiefly by their ratio in the original solution.

Presumably the evolution of sodium clays requires sea waters abnormally rich in sodium or depleted in other bases. Certainly the clays that are observed forming in contemporary shelf seas are predominantly illitic types, relatively impoverished in sodium and especially enriched in potash. (*See particularly* Grim *et al.*, 1949.) The experimental work of Kelly and Liebig (1934) substantiates these findings and seems to refute Taylor's suggestion (1929) that sodium clays found in some oil fields were formed in open seas.

The very fact that calcium, magnesium, and potassium possess higher replacing powers (energies of replacement) than sodium in the base-exchange process (Kelly, 1939) explains in large part why sodium clays are uncommon. For if, after sodium clays are formed, they are exposed to solutions containing cations of

[7] These considerations and many others in this paper depend upon the premise that actual changes in composition of sea water with time (from the period of Grenville sedimentation to the present) are, in terms of percentile composition, merely second-order differences. (*See especially* the discussion by Rubey, 1951.) This assumption obviously cannot be valid for all time and may be unreasonable for much of the Precambrian. Most aspects of the least-altered marbles in the Grenville series, as for example their gross and accessory-element composition, appear to substantiate the concept that Grenville seas contained about the same amounts of the common salts as do modern oceans. The composition of the marbles and associated layers are discussed more fully in Part III.

magnesium, calcium, or potassium, the sodium is exchanged for the other cation. On the other hand, if a sodium clay evolved in a basin of abnormally sodic water, and remained in this environment until buried by younger sediments, the odds of the clay's survival appear to be fair or good. Kelly and Liebig note that "it is difficult to leach a bed of sodium clay with water because sodium clay is highly impervious . . . owing to the fact that it tends to be highly deflocculated (1934, p. 360; *see also* Kelly, 1939, p. 454–458). Throughout deposition and diagenesis of the hypothetical beds, solutions from external sources would have very little opportunity to enter, until loading of the beds by younger rocks and the consequent compacting had ceased. By that time, of course, the beds would have reached a state of relative imperviousness.

Whether the sedimentary parent to the gneiss could have been a sodium clay can be no more than a speculation at this time. The concept appears about as tenable as that which postulates graywacke as the primary sediment, but more reasonable than the assumption that the gneiss evolved from either a tuff or a zeolitic rock. Obviously the final answer to the origin of the gneiss can come only from much additional, careful work.

Relation to Gneiss in the Grenville Series of Canada

The foregoing discussion emphasizes the need to reconcile the Adirondack data with, and relate them to, the heretofore suggested origins of quartz-biotite-feldspar gneisses in the Grenville series in Canada. Many workers in Canada have concluded that the major (biotitic) paragneiss(es) in the Grenville series represent "normal marine shales" of the well-sorted type.

The idea appears to stem from the work of Adams (1896, p. 96–102j) who compared analyses of three garnetiferous and sillimanitic gneisses, one relatively rich in biotite, from the Grenville series of the "Eastern Townships," Quebec (northwest corner of the Montreal sheet), to analyses of roofing slates from Great Britain and Switzerland with the comment that "these gneisses have the composition of slates" (p. 100j).

This conclusion, and from it the concept that the major paragneisses associated with the marble have about the same composition and represent typical argillaceous sediments, is endorsed by many subsequent workers, although seemingly upon quite limited data from a relatively localized segment of the Grenville series.

Paradoxically enough, in one of the most recent studies of rocks near the northern border of the inferred Grenville Subprovince (Wahl and Osborne, 1950), a quartz-biotite-andesine gneiss (some of which seems very similar to the least-altered Adirondack types) (Table 2) is classed as probably Timiskaming, in large part because:

> "the paragneisses are not exceedingly rich in garnet, and the tenor of this mineral along with that of such minerals as sillimanite, which was found in only one thin section, or cyanite, which does not occur at all, shows that it is unlikely that shale rocks were present in the Cawatose area. Throughout this report, the calcity of the feldspars has been emphasized. The anorthite content is relatively high and is a reflection of a considerable content of lime. Potassic feldspar is not abundant in the paragneisses, and is commonly related to the granitic material of the lit-par-lit injections" (p. 31).

In the six specimens of Cawatose gneiss of Canada from which modes were made (Wahl and Osborne, 1950, p. 17), plagioclase ranges from 26 to 68 per cent of the rock, averaging 50 per cent, quartz ranges between 8 and 31 per cent averaging 20 per cent, and biotite ranges between 9 and 49 per cent averaging 25 per cent. Comparison of these data with the modes of the least-altered Adirondack gneiss (Table 2) indicate an overlap in modal compositions. The paragneiss of Wahl and Osborne appears to be more variable in composition, however, and the specimens reported average less quartzose and more feldspathic and biotitic.

The average anorthite content of the feldspars as determined by Wahl and Osborne ranges from An_{22} to An_{54} and averages An_{32}. Consequently the feldspars are only slightly more calcic than that of the plagioclase in the least-injected gneiss of the Hyatt sector (An_{26}) and about the same composition as some specimens of gneiss north of Edwards, where sodic labradorite is not uncommon. The fact that Wahl and Osborne found a gneiss of this

composition—which would fit many metamorphosed Timiskaming graywackes—in no way implies its relationship to the Grenville series. Very possibly it is not a part of the Grenville series. Nevertheless to us it is surprising that this composition and mineral association, without appreciable garnet or sillimanite, should be raised as an argument for excluding a unit from the Grenville series. In fact, Osborne (1939) has described quartz-biotite-plagioclase gneisses from the Grenville series (at Montauban, Portneuf County, Quebec) that approximate in composition both the Adirondack gneiss and some of the more siliceous specimens of Cawatose gneiss (p. 715, Table 1). At Montauban, the four specimens of gneiss described contained quartz that ranged from 42 to 69 per cent and averaged 52 per cent, biotite that ranged from 8 to 23 per cent and averaged 16 per cent, and plagioclase[8] that ranged from 19 to 32 per cent and averaged 24 per cent. Only one of these contains appreciable sillimanite, and none contains more than 1.5 per cent garnet.

TABLE 13.—MODAL COMPOSITIONS OF QUARTZ-BIOTITE-FELDSPAR GNEISS FROM THE BROCKVILLE-MALLORYTOWN AREA, ONTARIO, AND THE AVERAGE OF 58 MODES OF ADIRONDACK GNEISS

W36, W44, and W69 are modes from Wright. Qb-Av represents the average of modes of Adirondack gneiss.

	W36	W44	W69	Qb-Av.
Quartz	59.5	50.0	51.0	38.0
Potash feldspar	10.0	18.5	19.2	13.0
Plagioclase	8.0	6.9	16.0	32.0
Biotite	21.2	20.6	31.0	15.0

The Cawatose gneiss described by Wahl and Osborne lies some 200 miles north of the Adirondacks, presumably near the margins of, or beyond, the carbonate-rich segment of the Grenville series. The paragneiss of the Montauban zone in Portneuf County, Quebec, is interlayered with thin marbles, but is almost 100 miles northeast of the Adirondacks. The data on the thicker paragneisses in the intervening area, especially those Canadian localities peripheral to the Adirondacks, are of perhaps greater pertinence. Although there are innumerable references to "paragneisses" and garnet-sillimanite gneisses in intervening areas, useful data are very rare. Only eight chemical analyses other than those originally published by Adams (1896) and less than a dozen modes are extant in the literature. There are scattered references to the mineralogy of gneissic units, but few of them permit even a very rough approximation of the composition of the unit, and almost none describes its dimensions or lithologic features in detail.

The data on gneisses just north of the Adirondacks, in southeastern Ontario, appear in discussions by Wright (1923, p. 15–18) and Miller and Knight (1914).[9]

Interestingly enough, certain of the data in both these reports are consistent with the possibility that a gneiss or gneisses much like the Adirondack version may occur in southern Canada. That is, there appears to be no published, impregnable reason for postulating an abrupt transition in sedimentary facies coincident with the International boundary.

The data on the gneiss of the Brockville-Mallorytown area are of special interest in that structural and stratigraphic considerations suggest this is a segment of the Adirondack gneiss. The specimens of this gneiss which Wright studied and described as "garnet and biotite gneiss" (1923, p. 16) have the reported modal compositions shown in Table 13 in columns W36, W44, and W69. In column Qb Av. we have added the average of 58 modes of Adirondack gneiss heretofore discussed.

Wright (1923, p. 16) notes that

> "These rocks as represented by W36, W44, W69, are distributed in small patches over the whole area and in many cases the outcrops are too small to represent on the map—at no place is a very large area of these rocks exposed and many of the outcrops are so granitized that thin sections or chemical analyses afford little information."

[8] Osborne does not report the kind of plagioclase, but Moorhouse (1941, p. 615) records compositions ranging from andesine to labradorite for plagioclases in paragneisses in the same area.

[9] A third paper (Baker, 1916) dealing with the Kingston area includes two analyses (not in the above count) of "green schists," but the brief accompanying discussion (p. 4, 5) suggests one rock is an amphibolite and the other an almost quartz-free biotite-orthoclase rock of obscure relations.

There are obvious compositional differences between the gneiss in the Brockville area and the least-injected types of gneiss of the Adirondacks. The Brockville gneiss as indicated by Wright's modes is more quartzose and biotitic and contains less feldspar than the average gneiss mapped in the northwest Adirondacks. Moreover, the plagioclase is described as oligoclase-albite which is slightly more sodic than that commonly found in the more biotitic facies of the Adirondack gneiss. However, specimens of the more biotitic layers in the Adirondack gneiss approach very closely the compositions in Wright's reports. In the Adirondacks, these are the layers inferred to be inoculated with iron as well as alkalis and silica by the advance waves of magma or fluids therefrom. The gneiss of the Brockville-Mallorytown area is literally engulfed in granite, and alterations of this same type may readily be inferred. On the other hand, the differences may reflect slight lateral variations in the composition of the original sediment.

Alternate reasons may exist for the differences reported, other than those ascribable to lateral variations in facies metasomatic changes or incorrect correlations. Almost any specimen of the gneiss will yield greatly exaggerated values for biotite if the section is cut at angles other than 90° to the foliation. Moreover the oligoclase in these rocks is remarkably clear, and is commonly mistaken for quartz in the course of micrometric traverses. It is no slur on Wright's abilities as a petrographer to suggest that either or both of these possibilities could have contributed to the high-quartz, high-biotite values he reports.

We hope to restudy the gneiss of the Brockville-Mallorytown area in the immediate future and to attempt to evaluate these alternatives. In any event, the reported differences are not great enough to modify the suggested correlation or the conclusions arrived at for the gneiss in the Adirondacks.

The other data of particular interest because of proximity to the Adirondacks appear in the work of Miller and Knight (1914) in southeastern Ontario.

Therein, three chemical analyses of relatively thick quartz-biotite-feldspar gneisses are given (Table 14). One or more of these rocks may be a part of the Hastings series rather than in the typical Grenville series, although they are described as the major biotitic paragneiss in the Grenville series at each of several localities. These analyses are assembled in Table 14 together with the analysis QbA, which is the composite of least-injected and least-altered layers of Adirondack gneiss.

TABLE 14.—CHEMICAL ANALYSES OF THREE QUARTZ-BIOTITE GNEISSES FROM SOUTHEASTERN ONTARIO AND THE ANALYSIS Qb-A OF ADIRONDACK GNEISS

	I	II	III	IV (QbA)
SiO_2	75.78	61.02	67.42	70.90
Al_2O_3	12.91	21.40	15.74	12.17
Fe_2O_3	.83	.37	.35	1.31
FeO	4.07	3.43	3.46	4.12
MgO	.53	.41	1.86	2.32
CaO	1.63	4.40	3.36	1.55
Na_2O	1.67	1.82	2.94	3.74
K_2O	1.10	2.52	1.73	2.87
H_2O-, H_2O+	1.51	2.23	3.55	.26
CO_2	.57	1.74	.31	
Total	100.60	99.34	99.72	99.24

I. Fine-grained gray to pinkish gneiss in the Grenville series, Belmont Lake area. Analyst not indicated. (Miller and Knight, 1916, p. 26.)

II. Gneiss or "graywacke" interlayered with quartzite and marble near Queensboro, Ontario. Analyst W. K. McNeill. (From Miller and Knight, 1914, p. 26.)

III. Quartz-biotite-feldspar gneiss associated with marble about 4 miles northeast of Madoc, Ontario. Analyst not indicated. (From Miller and Knight, 1914, p. 80.)

IV. Analysis of 24 least altered layers of quartz-biotite-oligoclase gneiss, southwest of Hyatt, N. Y. Analyst, Ledoux and Co.

Assuming the determinations of alkalis are correct (Fairbairn *et al.*, 1951) two of the three analyses given by Miller and Knight do not imply normal shales of the well-sorted type, although the one referred to as "graywacke" by the authors (1914, p. 91, and No. II, Table 14) does approach the composition of some shales.

The analysis numbered I in Table 14 is from the Belmont Lake area, west of Madoc,

Ontario. The rock is described as fine-grained with a gray to pinkish color and scattered interlayers of marble (p. 26).

Analysis II is of rock described as "graywacke" (p. 91) intimately associated with white quartzite and marble. This is actually the least like the analysis QbA of Adirondack gneiss and certainly least like a typical graywacke in chemical composition.

Analysis III is described as from a gray gneiss of medium grain and made up of acid plagioclase, microcline, quartz, biotite, muscovite, and a few grains of calcite. This is one of a series of interlayers which range from several to 800 feet wide and is associated with marble about 4 miles northeast of Madoc, Ontario (p. 80).

Analyses I and III certainly show no features strongly unlike those of QbA. Although the analyzed rocks may be completely unrelated to the Adirondack gneiss, they certainly do not reflect any marked differences, nor do they strongly suggest a rock derived from normal shales.

Other published references to gneisses that might represent a further extension of the major one in the Adirondacks, into southeastern Ontario, are confined to very general comments on dominant minerals or rock associations. Many of the thicker paragneisses in the Grenville series to the north and northwest of Kingston, Brockville, and Mallorytown are, for example, described as garnet paragneiss, micaceous schist, or garnet-sillimanite gneiss.

Seemingly no extremely thick, relatively monotonous gneissic unit is exposed or mapped. Such a unit could exist, but not be exposed, or may be so blurred by the igneous and metamorphic overprint as to be overlooked. The most likely alternative appears to be that an Adirondack-Brockville facies of the gneiss interfingers to the north and northwest with quartzite and marble, and possibly becomes less sodic in composition. These relations are implied by the numerous discussions of potassic paragneisses on the Grenville series with interlayered quartzite and limestone (*See, for example*, Wilson, 1919, p. 8, 9; Osborne, 1936, p. 207; Harding, 1942, p. 62, 85; 1947, p. 11, 12; Thomson, 1943, p. 7.)

Still another alternative and point of interest is raised by the comments of several authors (Wilson, 1925, p. 392–395; Osborne, 1936, p. 207; Harding, 1947, p. 11; and others) to the effect that the more southwesterly segments of the carbonate-rich Grenville series in Canada (Madoc area for example) are less completely metamorphosed than the rocks along and east of the Ottawa River. Wilson (1925, p. 394) notes:

> "The Grenville series in the western part of the belt is distinguished from that in the eastern part by ... its less metamorphosed condition and by the large proportion of mica schist and the relatively small proportion of sillimanite-garnet gneiss which it includes."

This raises the question whether the sillimanite-garnet facies along and east of the Ottawa River may not be a higher-rank metamorphic derivative of the "mica schists," or possibly of a rock originally not too unlike the Adirondack gneiss but now greatly modified through extensive interaction with granitic fluids at elevated temperatures. Without exception, the published chemical analyses, and most or all of the petrographic studies which purport to relate a major gneiss in the Grenville series to a normal shale parent, are of garnet-sillimanite paragneiss from along or east of the Ottawa River. Thus, in addition to the published analyses of Adams (1896, p. 101j) (and omitting from discussion the analyses in the work of Miller and Knight) we have found six analyses of paragneiss. Three of these (Wilson, 1925, p. 393) are from sillimanite-garnet gneiss in Papineau County, Quebec; a fourth, published first by Osann (1902) and republished by Wilson (1925, p. 393), is of a sillimanite-garnet gneiss on the south shore of the Ottawa River; a fifth analysis, also of sillimanite gneiss, is from the Shawinigan Falls District, Quebec (Osborne, 1936, p. 206). The sixth (Bain, 1923, p. 655) is from the La-Chute area where Osborne concludes the primary clastic sediments of the Grenville series were "sandstones and shales" (1936, p. 11). The analysis published by Bain shows very high values of Al_2O_3 (18.44) and ferrous iron (FeO = 8.42), and a silica content of only 55.91. On the other hand the Na_2O content (2.08) is 1.8 times that of K_2O. If these values

are essentially correct the gneiss can hardly represent either a common shale or argillaceous sandstone.

All the other analyzed rocks have at present a bulk composition much closer to common shales than, say QbA, but so do the sillimanitic segments of Adirondack gneiss which have evolved through interaction with magma at elevated temperatures along or in the central Adirondack massif. The question naturally arises, can some of the sillimanite-garnet gneisses of the Canadian localities which have compositions approaching shales have evolved much as have the Adirondack examples, from a parent rock of the composition of QbA, or from another rock of quite different composition. Presumably major gneisses in the Grenville series are derived from segments of somewhat different initial composition and possibly very different stratigraphic positions.

If the major gneissic unit(s) of the Ottawa River region are derived from much less sodic sediments than those inferred in the Adirondacks and at Brockville, however, the implied transitions in facies occur in a belt less than 35 miles wide—although possibly twice this as measured along relict bedding in the Grenville series. This seems to be a region worth careful study in determining the origins of the gneissic units.

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Short Notes

PHYSICS OF THEORIES OF OROGENESIS

By F. A. Vening Meinesz

Although in general the writer prefers not to reply to papers opposing his views—he gladly leaves the questions involved to the judgment of the readers—he wants to correct a statement made by Dr. A. E. Scheidegger (1953, Examination of the physics of theories of orogenesis: Geol. Soc. America Bull., vol. 64, p. 127–150) because he gives (p. 145) a curious misrepresentation of the writer's opinion, obviously based on a misunderstanding of the writer's text. The complete paragraph of the writer, quoted in part by Doctor Scheidegger, is taken from the text of a lecture given before the Geological Society of London and published in their Quarterly Journal of January 1948; it is:

"A direct consequence of the strength-limit is the counteraction of the instability which otherwise the cooling of the Earth would bring about. This cooling causes a lowering of the temperature at the surface of the convection layer, the upper part of this layer thus acquiring a greater density than the lower half. In the case of a Newtonian liquid, this would mean instability, as the slightest disturbance would start a convection-current. If, however, the layer possesses a certain strength, the disturbance must be powerful enough to overcome this strength before the current can be started. Such a disturbance could be provided by, for example, a difference of cooling in neighbouring areas. The possibility of convection is dependent, therefore, on other phenomena in addition to the normal temperature gradient caused by the cooling of the Earth, and its occurrence only in certain areas is understandable."

The writer's aim was to express that, besides a temperature gradient in a vertical sense leading to greater density overlying lesser density, a small disturbance of another kind is required for starting a current. For a Newtonian liquid this can be infinitely small; for rocks having a strength limit which must be overcome before flow can set in, it must have a finite value. So another phenomenon is then needed before a convection current can occur: it must have the effect of causing a finite difference of pressure in neighboring areas of the same horizontal planes.

This meaning becomes still clearer when the paragraph quoted is considered in connection with the preceding and following parts of the text. It must also be taken into account that the writer gave the lecture before an audience of geologists and had to abstain as much as possible from mathematical formulas.

The writer has been perfectly aware of Lord Rayleigh's result mentioned by him in his famous paper on convection (Philos. Mag., Dec. 1916) that for currents in viscous Newtonian liquids a minimum temperature gradient is needed dependent on the thickness of the layer and on several physical constants. The writer mentioned it, *e.g.*, on page 39 of his own publication in 1948 (Gravity expeditions at sea, vol. IV, 1948), but there was no reason to burden the lecture with this fact as it does not affect the reasoning. I do not think Doctor Scheidegger is right in supposing that this fact might explain the more or less periodic character of the tectonic processes in the Earth; if once the cooling had brought about a sufficient temperature gradient in the mantle and if this mantle had the properties of a Newtonian liquid, a current would have set in which would not have come to a stop by itself and which thus would have been stable.

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PHYSICS OF THEORIES OF OROGENESIS: A REPLY

BY A. E. SCHEIDEGGER

In his note, Mr. Vening Meinesz wishes to correct a representation of his views which was given by the writer in a paper which appeared in the Bulletin of the G.S.A., February 1953.

It was not the intention of the writer to present anything in his paper but the views of Mr. Vening Meinesz exactly as stated in the latter's note; he wishes to offer his apologies if he did not succeed therein.

The crux of the writer's discussion which seems to have been missed by Mr. Vening Meinesz, was *not* to suggest that the latter was unaware of the work done on Newtonian liquids, but to question the statement that in a plastic layer there must be a disturbance *additional* to a temperature gradient to start a convection current. There is only relatively little experimental evidence as to the properties of thermal hydrodynamics in plastics. In order to obtain an insight into such properties, the plastic bodies were compared with viscous ones whose behavior is better known. All the experimental evidence which was available to the writer (references were cited), seems to show that the thermo-hydrodynamics of viscous and plastic substances is essentially identical. Notably, a finite temperature gradient is required to start motion in both cases.

Thus, viscous bodies being seemingly not much different from plastic ones as far as thermal flow properties are concerned, the latter have been chosen to obtain an indication of what could happen in plastics. By this string of arguments it was reasoned that there is up to date no indication that one would need disturbances additional to vertical thermal gradients in (compressible) plastics in order to start convection currents. Hence, the whole argument of Mr. Vening Meinesz concerning his turnover mechanism was questioned at its base. It was not completely disrupted, though, but it was stated that, unless some physical corroboration can be supplied of the basic physical requirement, viz. of the necessity of stresses additional to thermal ones in order to start convection currents, it has to be designated as a hopeful speculation rather than as a scientific argument.

It is the writer's hope that the above explanation will clarify the original discussion in the writer's paper which was obviously not sufficiently explicit to prevent misunderstandings.